Arizona Geological Society Digest 22
2008

Tectonic influences on the spatial and temporal evolution of the Walker Lane: An incipient transform fault along the evolving Pacific – North American plate boundary

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ABSTRACT

Since ~30 Ma, western North America has been evolving from an Andean type margin to a dextral transform boundary. Transform growth has been marked by retreat of magmatic arcs, gravitational collapse of orogenic highlands, and periodic inland steps of the San Andreas fault system. In the western Great Basin, a system of dextral faults, known as the Walker Lane (WL) in the north and eastern California shear zone (ECSZ) in the south, currently accommodates ~20% of the Pacific – North America dextral motion. In contrast to the continuous 1100-km-long San Andreas system, discontinuous dextral faults with relatively short lengths (<10-250 km) characterize the WL-ECSZ. Cumulative dextral displacement across the WL-ECSZ generally decreases northward from ≥60 km in southern and east-central California, to ~25 km in northwest Nevada, to negligible in northeast California. GPS geodetic strain rates average ~10 mm/yr across the WL-ECSZ in the western Great Basin but are much less in the eastern WL near Las Vegas (<2 mm/yr) and along the northwest terminus in northeast California (~2.5 mm/yr).

The spatial and temporal evolution of the WL-ECSZ is closely linked to major plate boundary events along the San Andreas fault system. For example, the early Miocene elimination of microplates along the southern California coast, southward steps in the Rivera triple junction at 19-16 Ma and 13 Ma, and an increase in relative plate motions ~12 Ma collectively induced the first major episode of deformation in the WL-ECSZ, which began ~13 Ma along the N60°W-trending Las Vegas Valley shear zone. This shear zone developed parallel to plate motions and inboard of where the San Andreas system initially organized into a through-going structure. The Las Vegas shear zone accommodated ~60 km of right slip from ~13 to 6 Ma. N-S shortening and NE-striking sinistral faults in the Lake Mead region directly east of the shear zone may have partly accommodated collision of more mobile parts of the western Cordillera against the stable North American craton. In the late Miocene, the southern part of the transform shifted eastward into the Gulf of California (~13-6 Ma), the Big Bend of the San Andreas developed, and plate motions changed from ~N60°W to N37°W (11-6 Ma). Coincidentally (~11-6 Ma), dextral shear shifted westward in the WL-ECSZ from the Las Vegas shear zone to a NNW-trending belt in the western Great Basin (e.g., Mojave Desert block, southern and central Walker Lane). Dextral shear was favored in the western Great Basin because it paralleled the new plate motion, aligned more directly with the Gulf of California, and avoided the bottleneck in the Big Bend. By ~4 Ma, dextral shear had propagated northwestward into the northern Walker Lane (NW Nevada – NE California) in concert with the offshore northward migration of the Mendocino triple junction. The northern Walker Lane is the youngest, least developed part of

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Faulds, J.E., and Henry, C.D., 2008, Tectonic influences on the spatial and temporal evolution of the Walker Lane: An incipient transform fault along the evolving Pacific – North American plate boundary, *in* Spencer, J.E., and Titley, S.R., eds., Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: Arizona Geological Society Digest 22, p. 437-470.

the WL-ECSZ. Here, cumulative right slip decreases from ~25 km to zero northwest toward the southern Cascade arc. En echelon left-stepping dextral faults in this region are analogous to Riedel shears developed above a more through-going shear zone at depth. The strike-slip faults end in arrays of ~N-striking normal faults as dextral shear diffuses into extension. Coeval extension and dextral shear have induced slight counter-clockwise block rotations, which may ultimately rotate Riedel shears toward the main shear zone at depth. This process may facilitate hard linkage between Riedel shears and produce a through-going strike-slip fault.

The WL-ECSZ presently terminates northwestward near the southern end of the Cascade arc at approximately the same latitude as the Mendocino triple junction, suggesting that the San Andreas and WL-ECSZ are migrating northward at similar rates. Continued northward migration of the triple junction puts it on a collision course with the NW-propagating WL off the southern Oregon coast in ~7-8 Ma. At that time, the plate boundary will likely jump inland to the WL-ECSZ, similar to the late Miocene eastward shift of the southern part of the boundary into the Gulf of California.

The current tectonic setting represents one stage in the progressive dismembering of an Andean type margin through continued lateral growth and inland stepping of an evolving transform boundary. This process is slowly fragmenting the western margin of North America and transferring large slices of the continent to the Pacific plate. Evolving transform faults may therefore be an efficient means by which to generate exotic (i.e., far-traveled) terranes.

INTRODUCTION

Since ~30 Ma, western North America has been evolving from an Andean type margin to a transform boundary, as the contact between the North American and Pacific plates has progressively lengthened at the expense of the Farallon and related subsidiary plates (e.g., Atwater, 1970; Atwater and Stock, 1998). Growth of the dextral transform has been marked by the retreat of magmatic arcs, gravitational collapse of broad orogenic highlands inherited from the preceding convergent margin setting, and periodic inland steps of the developing transform (e.g., Coney and Harms, 1984; Jones et al., 1996, 1998; Atwater and Stock, 1998; Flesch et al., 2000). Most of the plate boundary strain is currently focused on the San Andreas fault system in coastal regions of California and the related dextral fault system within the Gulf of California (Fig. 1). In the western Great Basin, however, a system of dextral faults, known as the Walker Lane in the north (Stewart, 1988) and eastern California shear zone in the south (Dokka and Travis, 1990), currently accommodates ~20% of the Pacific – North America dextral motion, as evidenced by GPS geodetic data (Dixon et al., 1995, 2000; Hearn and Humphreys, 1998; Thatcher et al., 1999, Bennett et al., 2003; Oldow et al., 2001; Hammond and Thatcher, 2004, 2007; Kreemer et al., in press).

The Walker Lane – eastern California shear zone splays from the San Andreas fault system in southern California, shunting ~20% of the relative plate motion east of the Sierra Nevada block (Fig. 1). Much of the Walker Lane essentially accommodates dextral motion of the Sierra Nevada block relative to the central Great Basin. The entire system of dextral faults terminates, however, near the latitude of the Mendocino triple junction in northeast California at the south end of the Cascade arc and against the clockwise-rotating Oregon block. The coincidence between the northern end of the San Andreas fault system at the Mendocino triple junction and the inland termination of the Walker Lane in northeast California (Fig. 1) suggests that the Walker Lane is intimately related to the San Andreas.

However, the general style of deformation within the San Andreas fault system differs markedly from that within the Walker Lane and eastern California shear zone (e.g., Wesnousky, 2005b). Regionally extensive, interconnected dextral faults, some with strike lengths exceeding several hundred kilometers, characterize the 1,100-km-long San Andreas system, whereas discontinuous, en echelon dextral faults, typically with strike lengths of less than ~150 km comprise the Walker Lane – eastern California shear zone (Figs. 1 and 3). The inferred magnitude of displacement also differs significantly on the two systems, with more than 400 km documented for parts of the San Andreas system versus a maximum of ~100 km for anywhere within the Walker Lane – eastern California shear zone. These contrasts epitomize the mature, well developed nature of the San Andreas versus the youthful, incipient character of the Walker Lane. Thus, the Walker Lane represents one of the least developed parts of the Pacific – North America transform margin. As such, it is a natural laboratory for studying the incipient development and

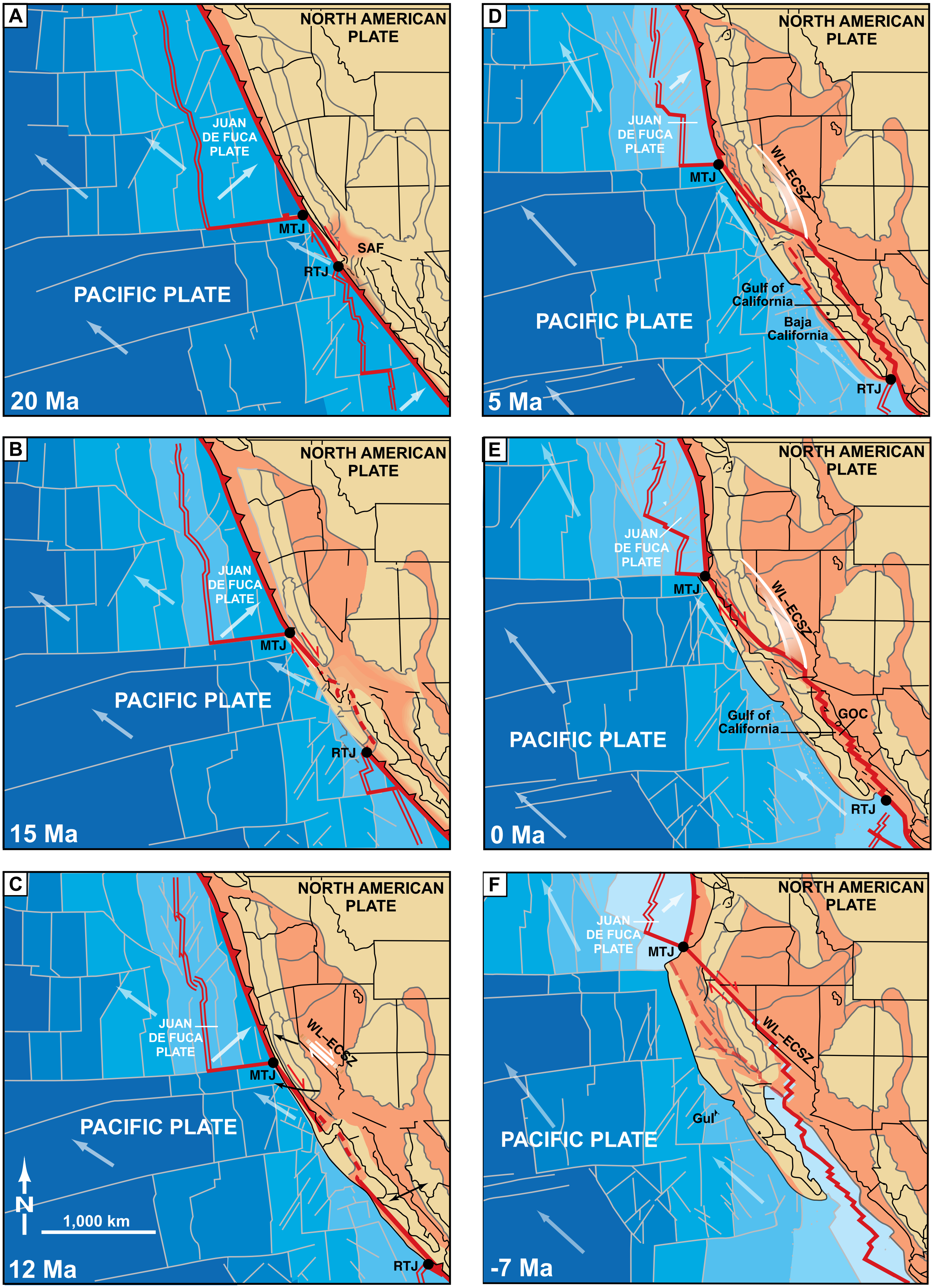
A
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Figure 2 (left). Time panels showing the evolution of the Pacific – North American transform boundary since ~20 Ma. The Juan de Fuca plate is the remnant of the Farallon plate. Double red lines are mid-ocean ridges. MTJ, Mendocino triple junction; RTJ, Rivera triple junction. A through E are modified slightly from Atwater (http://emvc.geol.ucsb.edu/download/nepac.php) and represent interpolations based on reconstructions by Atwater and Stock (1998). The most confident reconstructions are at 20.1, 10.9, 5.1, and 2.6 Ma (T. Atwater, written communication, 2008). F is our interpretation of the future development of the plate boundary. Dark orange areas denote areas of extension within the Basin and Range province. Lighter to darker shades of blue indicate relative ages of oceanic crust from youngest to oldest, respectively. A. 20 Ma – The San Andreas fault system is still relatively immature and only extends along the southern California coast. B. 15 Ma – The San Andreas has grown southward significantly as several microplates along southern California have been captured by the Pacific plate and the Rivera triple junction has jumped to the south. C. 12 Ma – Extensive southward lengthening of the San Andreas has been accommodated by a second, 1,000 km southward jump in the Rivera triple junction. The Las Vegas Valley shear zone (and possibly Stateline fault system) begin to form inland of a well organized, relatively mature segment of the San Andreas system. D. 5 Ma – The entire southern part of the San Andreas system has now shifted eastward to the Gulf of California, thereby generating a large restraining bend (i.e., the Big Bend) in southern California. Deformation in the Walker Lane – eastern California shear zone has shifted westward to the western Great Basin, more in alignment with the Gulf of California. E. 0 Ma (today) – Gulf of California has opened while the Mendocino triple junction has migrated northward ~3 cm/yr. The Walker Lane – eastern California shear zone now accommodates ~20% of the plate motion and appears to be growing northward in concert with the San Andreas. F. -7 Ma – Projected future development of the Pacific – North American transform, whereby the northward propagating Mendocino triple junction and Walker Lane – eastern California shear zone collide off the southern Oregon coast. This may herald a large eastward jump in the primary transform boundary to the Walker Lane, analogous to the eastward shift into the Gulf of California along the southern part of the system ~13-6 Ma.

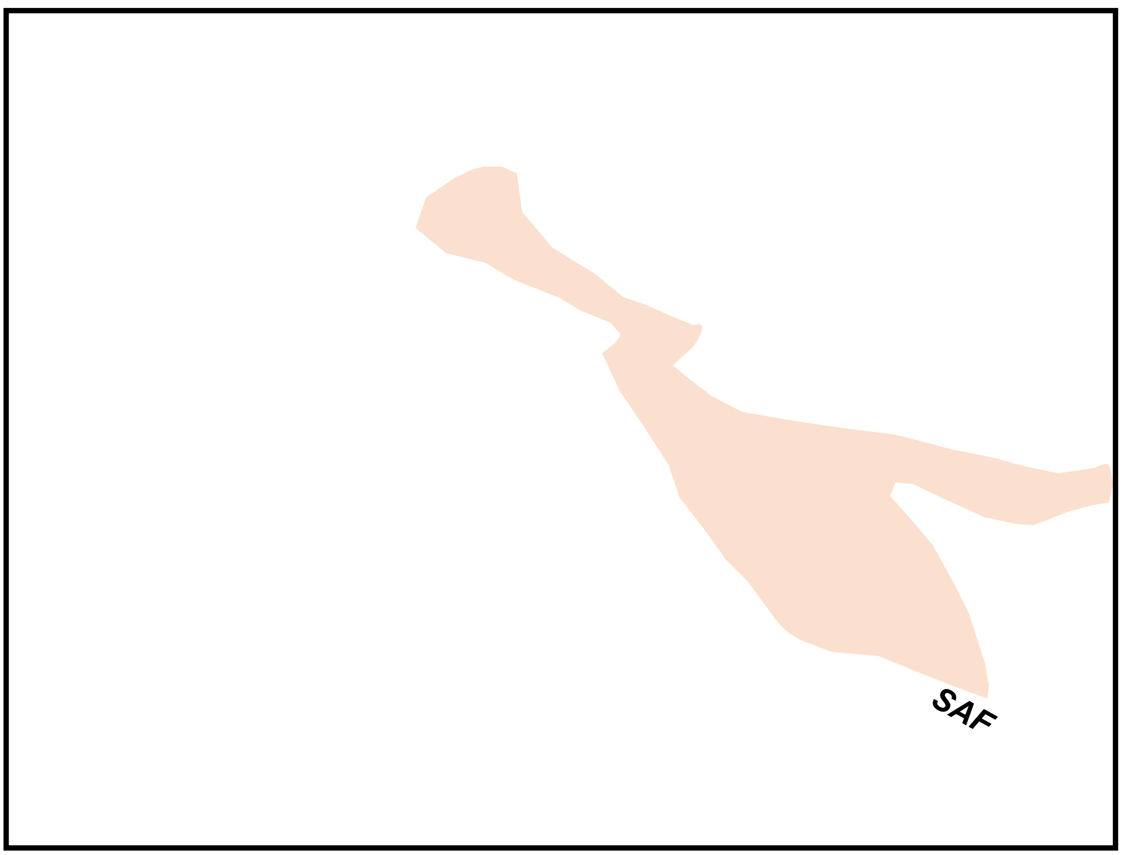
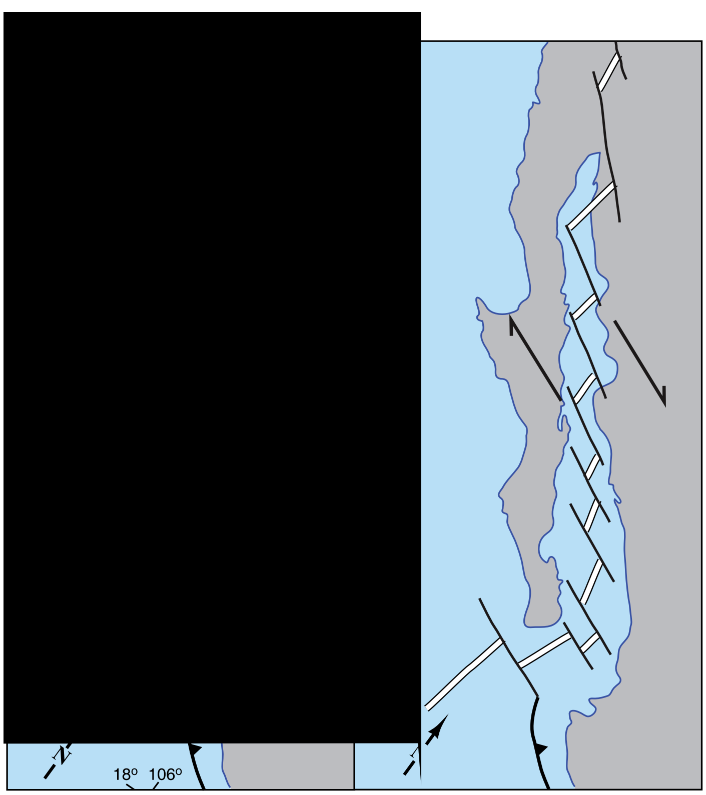


Figure 3. Oblique panoramic computer-generated image of the physiography of the southwestern U.S. courtesy of Dr. William A. Bowen - California Geographical Survey (http://geogdata.csun.edu). The Walker Lane is marked by an abrupt change in topographic grain in the western Great Basin, whereby north- to north-northeast-trending basins and ranges in the Basin and Range province give way to a more heterogeneous terrain dominated by north-northwest to northwest-trending topography. Note the continuity of the San Andreas fault system versus the less organized pattern of faulting in the Walker Lane – eastern California shear zone, which is shaded in transparent orange. BB, Big Bend in San Andreas fault system; BRP, Basin and Range province; CA, Cascade arc; SAF, San Andreas fault; SN, Sierra Nevada-Great Valley block; OB, clockwise-rotating Oregon block; ST, Salton trough; TR, Transverse Ranges (group of approximately east-trending ranges in Big Bend area);WA, north-south shortening belt in western Washington at north end of the Oregon block.

This is followed by more detailed discussion of the spatial and temporal evolution of individual domains within the Walker Lane. We then synthesize this information to formulate a conceptual structural and tectonic model for the overall development of the Walker Lane – eastern California shear zone in the context of plate boundary deformation.

SAN ANDREAS FAULT SYSTEM – GULF OF CALIFORNIA

The San Andreas fault system and Gulf of California collectively form the primary boundary between the Pacific and North American plates between northern California and central Mexico. The San Andreas fault system is a complex right-lateral transform consisting of late Cenozoic dextral faults and subsidiary structures, such as folds and sinistral, reverse, and normal faults (e.g., Powell et al., 1993). This system currently accommodates ~39 mm/yr of dextral motion between the Pacific and North American plates (Freymuller et al., 1999; Argus and Gordon, 2001). The 1,100 km long San Andreas fault is the centerpiece of this fault system as it links the Mendocino triple junction on the north with the group of spreading axes and dextral transform faults in the Gulf of California and Salton trough on the south (Fig. 1). In addition to the San Andreas fault itself, many other dextral faults within the system exceed several hundred kilometers in length (e.g., Graymer et al., 2002; Dickinson et al., 2005). Estimates of total dextral offset along the San Andreas fault system range from 435 to 730 km north of the Transverse Ranges and from 250-350 km south of the Transverse Ranges (see Powell et al., 1993 and references therein). A series of dextral transform faults, ranging from <50 km to ~250 km long, also comprises the Gulf of California, but in contrast to the San Andreas system, the individual transform faults are linked by small spreading segments (Fig. 1). The transform system in the Gulf currently accommodates ~51 mm/yr of dextral motion and has amassed ~300 km (Oskin and Stock, 2003) or 450-500 km (Fletcher et al., 2004, 2007) of total displacement. The San Andreas fault system and Gulf of California effectively merge in the Salton trough region of southern California (Fig. 1). From the beginning of its contact with the North American plate, the Pacific plate has moved obliquely to the transform margin, thus requiring components of motion both parallel and perpendicular to the transform (Fig. 4A; Hausback, 1984; Stock and Hodges, 1989). East-northeast extension in the Basin and Range probably accommodated the perpendicular component while also facilitating gravitational collapse of the existing orogenic highlands.



As documented in various plate reconstructions, the San Andreas transform began developing ~30 Ma as the Pacific plate came into contact with North America through the demise of the intervening Farallon plate (Atwater, 1970; Severinghaus and Atwater, 1990; Atwater and Stock, 1998). With continued subduction and demise of the Farallon plate, the transform has progressively lengthened to both the north and south over the past 30 Ma through the respective migrations of the Mendocino and Rivera triple junctions (Fig. 2). Transform growth, however, has not been linear or continuous along a specific plate boundary. Instead, the San Andreas system has not only stepped inland through time but also experienced several discrete lateral jumps parallel to the plate boundary. Some of the more notable events along the evolving transform boundary include: 1) elimination of several small microplates off the southern California coast and ensuing development of a more through-going San Andreas fault by ~16 Ma (Nicholson et al., 1994); 2) discrete southward steps in the Rivera triple junction at 19-16 Ma and ~13 Ma (Stock and Hodges, 1989; Atwater and Stock, 1998); 3) an increase in relative plate motion ~12 Ma (Atwater and Stock, 1998); 4) a significant inland jump of the southern part of the transform from off the western coast of Baja California to the Gulf of California between ~13 and 6 Ma (Hausback, 1984; Stock and Hodges, 1989; Fletcher et al., 2007); 5) subsequent opening of the Gulf of California (Oskin et al., 2001; Oskin and Stock, 2003) and development of the large restraining bend in the San Andreas fault system in southern California since at least ~6 Ma (e.g., Powell et al., 1993; Ingersoll and Rumelhart, 1999); and 6) a change in relative plate motions from ~11 to 6 Ma (Atwater and Stock, 1998).

The first event involved the fragmentation of remnant parts of the Farallon plate into various microplates as the east Pacific rise approached the western margin of North America (e.g., Fig. 2A, B; Atwater, 1989; Nicholson et al., 1994; http://emvc.geol.ucsb.edu/download/nepac.php). The development of the microplates induced several complex interactions between the Pacific and North American plates, which included large-magnitude rotation of the western Transverse Ranges and initiation of parts of the San Andreas transform as a low-angle fault system (Nicholson et al., 1994). These microplates also initially precluded development of a more through-going, continuous transform fault. Ultimately, the various microplates off the southern California coast were progressively captured by the Pacific plate between ~20 and 16 Ma. Thus, by ~16 Ma a relatively continuous San Andreas fault system had developed through much of central and southern California (Fig. 2B).

Although the Mendocino triple junction at the north end of the transform has generally migrated progressively northward at ~3 cm/yr since the Miocene, the Rivera triple junction on the south has progressed southward mostly in a series of jumps (Fig. 2A-C). Notable steps occurred between ~19 and 16 Ma, when the Rivera triple junction jumped from off the northern coast of Baja California to the central coast, and ~13 Ma, when it jumped ~1000 km southward from the central coast to what is now the mouth of the Gulf of California (Stock and Hodges, 1989; Atwater and Stock, 1998).

The effect of the southward jump in the Rivera triple junction ~13 Ma on the Gulf of California has been interpreted in two ways (Fig. 4). Hausback (1984) and Stock and Hodges (1989) suggested that the oblique motion of the Pacific plate relative to the North American plate was partitioned into east-northeast extension within what is now the Gulf of California (proto-Gulf rifting that formed the Gulf Extensional Province; Gastil et al., 1975) and ~325 km of dextral slip along the Tosco-Abreojos fault west of Baja California (Spencer and Normark, 1979). According to this interpretation, transform displacement remained outboard of the Gulf of California until ~6 Ma, at which time it jumped into and began to open the Gulf (Lonsdale, 1991; Oskin and Stock, 2003). Supportive evidence for this interpretation is that a major episode of east-northeast extension affected the area surrounding the Gulf beginning ~13 to 12 Ma (e.g., Stock and Hodges, 1989; Ferrari, 1995; Lee et al., 1996; Nieto-Samaniego et al., 1999; Henry and Aranda-Gomez, 2000) and that matching of ignimbrites across the northern Gulf of California indicate that all northwest-directed opening in the north has occurred since 6 Ma (Oskin et al., 2001; Oskin and Stock, 2003). The alternative explanation is that strike-slip faulting began in what is now the Gulf of California as early as 12-10 Ma, or approximately coincident with the southward jump of the Rivera triple junction, and that all oblique motion has been accommodated within the Gulf (Fletcher et al., 2007). Fletcher et al. (2007) concluded that <150 km of the required strike-slip displacement has occurred along the Tosco-Abreojos fault. Fletcher et al. (2004) also found 450 to 500 km of total tectonic transport across the mouth of the Gulf, more than could have occurred since 6 Ma alone. Additionally, Gans et al. (2006) cited evidence for right-lateral strike-slip faulting in coastal Sonora, east of the Gulf, by 9 Ma.

The evolution of the Gulf of California, especially the timing and distribution of northwest-striking dextral displacement and east-northeast extension, remains a topic of considerable debate and active research. However, many areas in the Gulf extensional province underwent east-northeast extension beginning ~13-12 Ma and have not undergone subsequent strike-slip faulting (Fig. 4A; e.g., Stock and Hodges, 1989; Ferrari, 1995; Lee et al., 1996; Nieto-Samaniego et al., 1999; Henry and Aranda-Gomez, 2000; Ferrari et al., 2007). Therefore, both interpretations require strain partitioning, the differences being into what regions and at what scale. Was transform faulting primarily or entirely along the Tosco-Abreojos fault until 6 Ma (Hausback, 1984; Stock and Hodges, 1989) or primarily or entirely within the Gulf since ~12 Ma (Fletcher et al., 2007; Gans et al., 2006)?

Although the timing is debated, it is clear that the southern part of the Pacific – North American transform had jumped inland from the Tosco-Abreojos fault off the western coast of Baja California to the Gulf of California by ~6 Ma. Nearly 300 km of dextral offset has occurred across the northern part of the Gulf since the latest Miocene (Oskin and Stock, 2003). The eastward shift of the southern part of the transform into the Gulf and Salton trough and subsequent northward translation of Baja California induced a broad left step or restraining bend in the right-lateral San Andreas fault system in southern California known as the Big Bend (Figs. 1 and 3; Hill and Dibblee, 1953). Major approximately east-trending folds and reverse faults within the western Transverse Ranges and adjacent regions have accommodated significant north-south shortening across the Big Bend region (e.g., Morton and Yerkes, 1987; Morton and Matti, 1987), primarily since ~6 Ma (Ingersoll and Rumelhart, 1999). Within the Big Bend region, the San Andreas fault may be slowly rotating to an unfavorable position to accommodate slip, which may be partly compensated by developing dextral faults farther east in the southern Mojave Desert block (Nur et al., 1993; Du and Aydin, 1996).

It is noteworthy that during the Miocene, roughly coincidental with eastward shift of the southern part of the transform into the Gulf of California, both the rate and direction of relative motion changed between the North American and Pacific plates. Global plate-circuit solutions indicate an initial change in rates from ~33 mm/yr to ~52 mm/yr at ~12 Ma. This was followed by a change in direction of motion from ~N60°W to N37°W at ~11-6 Ma (Atwater and Stock, 1998). This change in plate motions appears to approximately coincide with a change in relative motion from east-west to more northwesterly of the Sierra Nevada – Great Valley block relative to the Colorado Plateau (Wernicke and Snow, 1998; Atwater and Stock, 1998).

WALKER LANE – EASTERN CALIFORNIA SHEAR ZONE

The Walker Lane (or Walker Lane belt) and eastern California shear zone are overlapping regions of northwest-striking right-lateral shear within the western part of the Basin and Range province (Stewart, 1988; Dokka and Travis, 1990). Different geologists have used the terms differently, and their definitions have evolved through time. The following discussion reviews the original definitions and subsequent use of the terms.

The Walker Lane was first identified based on topography as the region in the western Great Basin of diversely oriented ranges distinguished from the regular north-northeast-trending ranges of the central Great Basin (Fig. 3; Gianella and Callaghan, 1934; Billingsley and Locke, 1939, 1941; Locke et al., 1940). Stewart (1988) provided the first general definition of the Walker Lane as a northwest-trending belt from northeastern California through western Nevada to the Garlock fault on the southwest and Lake Mead on the southeast. He divided the Walker Lane into nine structural blocks based on the characteristic structural style (Fig. 5A). Most of these blocks contain or are bounded by either northwest-striking dextral faults (Pyramid Lake, Walker Lake, Inyo-Mono, and Spring Mountains) or northeast-striking sinistral faults (Carson, Spotted Range-Mine Mountain, and Lake Mead). The Excelsior-Coaldale block is a roughly east-west belt where right-lateral displacement on northwest-striking faults of the Walker Lake block is transferred westward to similar faults of the Inyo-Mono block. This area is also termed the Mina deflection and coincides with a major bend in pre-Cenozoic structural trends and possibly the edge of the Precambrian craton (Fig. 1; Kistler and Peterman, 1973; Farmer and dePaolo, 1983; Oldow et al., 1989; Oldow, 1992). The Goldfield block is characterized by the absence of major strike-slip faults, has apparently undergone little or no dextral shear, and probably should not be considered part of the Walker Lane.

More recently, the Walker Lane has been divided into northern, central, and southern parts (Hardyman and Oldow, 1991; Oldow, 1992; Faulds et al., 2005a; Wesnousky, 2005a). The northern Walker Lane has typically included the Carson and Pyramid Lake domains (Fig. 5). The Walker Lake and Excelsior-Coaldale (i.e., Mina Deflection) blocks constitute the central Walker Lane. The southern Walker Lane consists of the Inyo-Mono, Spring Mountains, and Lake Mead blocks. Wesnousky (2005a) added a northern California shear zone that encompasses several northwest-striking faults with known or suspected right-lateral displacement that lie west and northwest of the Pyramid Lake block.

To the south, the Walker Lane merges with the eastern California shear zone that, in turn, connects with the San Andreas fault system in southern California (Figs. 1 and 3; Dokka and Travis, 1990; Dixon et al., 1995). Dokka and Travis (1990) defined the eastern California shear zone to include the northwest-striking dextral faults of the Mojave Desert as well as the southern Death Valley and Furnace Creek fault zones. The latter two faults lie within Stewart's (1988) Inyo-Mono block and the southern Walker Lane. Although Dokka and Travis (1990) did not discuss the Owens Valley area or Fish Lake Valley fault (the northern continuation of the Furnace Creek fault zone), many subsequent workers have included them in the eastern California shear zone (Reheis and Dixon, 1996; Lee et al., 2001a, b; Guest et al., 2007; Le et al., 2007). Thus, the area between the Garlock fault and northern Owens Valley and White Mountains is interchangeably the southern Walker Lane or "northern" eastern California shear zone. Hearn and Humphreys (1998) pointed out that most of what many call the eastern California shear zone lies within the earlier defined Walker Lane.

Adopted nomenclature

The Walker Lane and eastern California shear zone are clearly parts of the same intracontinental shear zone that accommodates ~20% of the Pacific – North American plate motion. The two terms are currently used interchangeably and continue to serve as adequate names for parts of the broader shear zone. However, for ease of discussion in this paper we term those parts of the shear zone north of the Garlock fault as the Walker Lane (after Stewart, 1988) and the region south of the Garlock fault as the eastern California shear zone (similar to Dokka and Travis, 1990).

Figure 5B and Table 1 portray the subdivisions of the Walker Lane – eastern California shear zone used in this paper. For parts of the system, we have slightly modified previous usage of terms. For example, we have included the Spring Mountains, Lake Mead, and Spotted Range-Mine Mountain blocks of Stewart (1988) in a separate region referred to as the eastern Walker Lane, because the apparent timing and style of deformation in this region differs somewhat from those parts of the system farther west. In addition, we refer to the Spring Mountains block of Stewart (1988) as the Las Vegas domain and include this domain in the group of blocks dominated by northwest-striking dextral faults, because it is bounded by the right-lateral Las Vegas Valley shear zone and Stateline fault system (Fig. 5B). Thus, our eastern Walker Lane contains


A
42°N
36°N
San Andreas Fault
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100 km
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Dominantly [redacted]

Table 1. Domain Characteristics, Walker Lane-Eastern California Shear Zone

Domain	Strain Character	Width of Domain	Fault Length	Rotation (Sense/Amount)	Dextral Slip Total	Timing of Deformation	GPS Dextral Strain Rate	Stage
Northern Walker Lane								
Modoc Plateau	Dextral – distributed	~80 km	<65 km	Not determined	Minimal	4 Ma? – Recent	2.5 mm/yr	1
Pyramid Lake	Dextral – left stepping	45-80 km	50-100 km	CCW/15-20°	20-25 km	4 Ma – Recent	10 mm/yr	2
Carson Domain	Sinistral, orocline	~80 km	25-100 km	CW/90-100°	30+ km	9 Ma – Recent	10 mm/yr	N/A
Central Walker Lane								
Walker Lake	Dextral – left stepping	~35-80 km	12-95 km	Not determined	40-60 km	10 Ma – Recent	10 mm/yr	2
Mina Deflection	Sinistral – distributed	~80 km	20-40 km	CW/≥20°	40-60 km	11 Ma – Recent	10 mm/yr	N/A
Southern Walker Lane	Dextral	50-120+ km	50-250 km	CW/50-80° locally	40-100 km	10 Ma – Recent	>10 mm/yr	3
Mojave Desert	Dextral	150 km	40-125 km	CW/25-67°	65 km	11 Ma – Recent	12 mm/yr	2
Eastern Walker Lane								
Spotted Range-Mine Mt	Sinistral – distributed	30-60 km	5-25 km	Not determined	<5 km?	13-6? Ma	Minimal	N/A
Las Vegas	Dextral, orocline	~80 km	40-200 km	CW/90-100°	60-90 km	13-6 Ma	<1.5 mm/yr	3
Lake Mead	Sinistral – distributed	30-45 km	20-50 km	CW/0 to locally >50°	65 km	13-6 Ma	<1 mm/yr	N/A

Notes: CCW, counterclockwise; CW, clockwise. Timing of deformation shows only the main episode. Stage refers to inferred stage of development, with #1 the least developed and #3 the most mature (see text for details). Belts of east- to northeast-striking sinistral faults were not evaluated for stage of development.

Similar to the Gulf of California, much of the Walker Lane – eastern California shear zone and neighboring parts of the western Basin and Range province underwent middle to late Miocene approximately east-west extension followed or accompanied by dextral faulting (Stewart and Diamond, 1990; Stewart, 1992; Stockli et al., 2000, 2003; Henry et al., 2007). Over the past 10 to 15 Ma, Basin and Range normal faulting has advanced westward across the western Great Basin into the Sierra Nevada (Saltus and Lachenbruch, 1991; Dilles and Gans, 1995; Stockli et al., 2001; Henry and Perkins, 2001; Surpless et al., 2002). An episode of low-magnitude extension at ~13-12 Ma generated a series of large, generally shallow basins along a distance of more than 300 km in what is now the Walker Lane east of the Sierra Nevada block (Stewart, 1988, 1992; Dilles and Gans, 1995; Stockli et al., 2003; Henry and Perkins, 2001). We suggest that, as with the Gulf of California, this extension probably also resulted from the southward jump in the Rivera triple junction and subsequent partitioning of oblique Pacific plate motion relative to the North American plate (Fig. 4A). Although much of the Walker Lane was north of the transform margin at ~12 Ma (Fig. 2C), the perpendicular, east or east-northeast component would not have been limited to a block bounded by the two triple junctions unless major continental transverse faults formed adjacent to both triple junctions.

The Sierra Nevada block probably rotated clockwise about a pole north of the region between the triple junctions so that the North American plate kept in contact with the Pacific and Juan de Fuca plates (Fig. 2), similar to the present day rotation of western Oregon (Wells et al., 1998; Svarc et al., 2002). Reconstructions showing that the Sierra Nevada underwent ~10° of clockwise rotation between ~16-14 Ma and 8-6 Ma, with most between ~12 and 10 Ma (Wernicke and Snow, 1998; McQuarrie and Wernicke, 2005), support the rotational origin of the contemporaneous extension. This is consistent with but does not prove the inferred relationship between extension and plate motion partitioning. Total extension from this rotation was small and should have diminished northward, toward the pole of rotation. However, estimates of total east-west extension within the Walker Lane during this 13-12 Ma, pre-strike-slip episode are sparse. Wernicke and Snow (1998) estimated 110 km of east-west extension between ~16 and 10 Ma at the latitude of Las Vegas, mostly within what is now the Walker Lane. Wernicke and Snow (1998) and McQuarrie and Wernicke (2005) inferred only northward translation of the Sierra Nevada after ~8-6 Ma.

As in the Gulf of California, when dextral faulting began in the Walker Lane is controversial and not clearly resolved in all areas. At one extreme, Hardyman (1980), Ekren et al. (1980), and Dilles and Gans (1995) estimated that Cenozoic strike-slip faulting began ~25 Ma in the central Walker Lane. On the other hand, Henry et al. (2007) suggested that major strike-slip faulting in the northern Walker Lane began since ~3.5 Ma. In most areas, strike-slip faulting appears to have initiated in late Miocene time between ~13 and 6 Ma (e.g., Dokka and Travis, 1990; Duebendorfer and Simpson, 1994; Schermer et al., 1996; Cashman and Fontaine, 2000; Faulds et al., 2005a). Constraints on the timing of deformation within various parts of the Walker Lane and eastern California shear zone are discussed in greater detail below.

It is clear that extension coincided with strike-slip faulting throughout the Walker Lane region. However, the extension direction shifted from ~east-west to west-northwest during late Miocene time (Zoback et al., 1981) roughly in conjunction with the onset of strike-slip faulting. Thus, the Walker Lane contains a complex system of kinematically related and broadly coeval northwest-striking dextral faults and north- to north-northeast-striking normal faults (e.g., Oldow, 1992; Faulds et al., 2004a, 2005b), as well as east-northeast-striking sinistral-normal faults (e.g., Wesnousky, 2005a; Sturmer et al., 2007). Many of these faults have been active in the Quaternary (e.g., dePolo et al., 1996, 1997). In contrast to the Gulf of California and San Andreas fault system, however, the Walker Lane – eastern California shear zone does not accommodate the bulk of plate boundary motion nor have the major strike-slip faults within the region evolved into major through-going structures several hundreds of kilometers in length.

DOMAINS OF THE WALKER LANE – EASTERN CALIFORNIA SHEAR ZONE

In this section, we review the geometry, displacement, and timing of dextral faulting for several parts of the Walker Lane – eastern California shear zone (Fig. 5B), including 1) the eastern Walker Lane (Las Vegas, Lake Mead, and Spotted Range-Mine Mountain domains), 2) Mojave Desert domain, 3) southern Walker Lane, 4) central Walker Lane (Walker Lake domain and Mina deflection), and 5) northern Walker Lane (Carson, Pyramid Lake, and Modoc Plateau domains). Table 1 summarizes the salient characteristics of each domain.

Eastern Walker Lane

The eastern Walker Lane is a discrete arm of strike-slip deformation that extends southeastward from the main branch of the Walker Lane – eastern California shear zone through the central Basin of Range province of Wernicke (1992) to nearly the western margin of the Colorado Plateau (Figs. 1, 3, and 5B). It consists of three distinct domains, the right-lateral Las Vegas domain, bounded by the Las Vegas Valley shear zone and Stateline fault system, and left-lateral Lake Mead and Spotted Range – Mine Mountain domains (Fig. 6). This region experienced large-magnitude approximately east-west extension in middle to late Miocene time (e.g., Wernicke and Snow, 1998). Most workers have associated the strike-slip deformation in the Las Vegas and Lake Mead domains to major transfer zones associated with large-magnitude extension (e.g., Liggett and Childs, 1977; Guth, 1981; Duebendorfer and Black, 1992; Duebendorfer and Simpson, 1994; Duebendorfer et al., 1998) or to structural rafting on a ductilely flowing substrate (Anderson et al., 1994), as opposed to plate boundary motions. However, Stewart (1988) included the entire region within the Walker Lane, and Guest et al. (2007) suggested that the Stateline fault system was part of the eastern California shear zone. In contrast to other parts of the Walker Lane – eastern California shear zone, the eastern Walker Lane was primarily active in the middle to late Miocene and has experienced relatively minor deformation in the Quaternary. GPS geodetic strain rates across this region are relatively minor, with an extension rate of ~1.6 mm/yr at 37°N latitude (Kreemer et al., 2008) and dextral shear of ~1 mm/yr across parts of the Stateline fault system (Wernicke et al., 2004; Hill and Blewitt, 2006).

Las Vegas domain. The Las Vegas domain consists of two northwest-striking right-lateral fault zones, the Las Vegas Valley shear zone and Stateline fault system, and the intervening Spring Mountains block, which has experienced relatively little late Cenozoic deformation (Fig. 5B). The Las Vegas Valley shear zone is a major right-lateral fault zone that extends across much of southern Nevada from the western Lake Mead area on the southeast to the Spotted Range on the northwest (Fig. 6; Longwell, 1960, 1974; Burchfiel, 1965; Wernicke et al., 1982). It trends ~N60°W, exceeds 100 km in length, and is ~30 km in width (Table 1). The shear zone essentially bounds both Las Vegas Valley and the Spring Mountains block of Stewart (1988) on the north. Belts of east- to northeast-striking left-lateral faults lie at both the east and west ends of the Las Vegas Valley shear zone (Fig. 6), the Lake Mead fault system and Spotted Range-Mine Mountain domains, respectively. A broad zone of oroclinal flexuring, as much as 45 km wide and affecting many of the larger mountain ranges in southern Nevada (e.g., Spring Mountains, Sheep Range, and Desert Range), marks the shear zone and reflects as much as 90-100° clockwise rotation (Fig. 6; Nelson and Jones, 1987; Sonder et al., 1994). Most of the shear zone is covered by late Miocene to recent sedimentary deposits in Las Vegas Valley, but gravity and seismic reflection data indicate several right steps and associated small but locally deep pull-apart basins along the shear zone in the northern part of Las Vegas Valley (Fig. 6; Langenheim et al., 2001).

The Las Vegas Valley shear zone has accommodated >60 km of dextral shear. Correlation of Sevier-age thrust faults and the bending of Paleozoic strata within the oroclinal flexure constrain the magnitude of offset, with ~23 km of actual slip beneath Las Vegas Valley and 20-25 km of bending on each side of the shear zone within the oroclinal flexure (Fig. 6; Burchfiel, 1965; Longwell, 1974; Wernicke et al., 1982). Liggett and Childs (1977) and Guth (1981) suggested that the Las Vegas Valley shear zone served as a transform-like structure separating spatially discrete belts of extension to the north and south of the zone.

Stratigraphic and structural relations indicate that most of the deformation along the Las Vegas Valley shear occurred between ~13 and 6 Ma. In the southern Las Vegas Range within a strongly rotated part of the oroclinal flexure, an ~16 to 12 Ma sedimentary sequence is as highly deformed as underlying Paleozoic strata, suggesting that dextral shear postdates ~12 Ma (Deibert, 1989). In the Frenchman Mountain area along the southeastern part of the shear zone, 19 to 13 Ma sedimentary strata are as highly deformed as Paleozoic strata, ~11.6 strata are less deformed, and ~6 Ma strata are only mildly deformed (Fig. 7; Castor et al., 2000; Duebendorfer, 2003; Duebendorfer and Simpson, 1994). Although numerous springs mark its approximate location, Quaternary fault scarps have not been observed along the shear zone. GPS geodetic data suggest strain rates of <1.3 mm/yr in the region (C. Kreemer, unpublished data, 2008). Thus, it appears that most of the activity on the Las Vegas Valley shear zone occurred in middle to late Miocene time, between ~13 and 6 Ma.

Exposures of the Las Vegas Valley shear zone are rare. The only mapped surface trace lies near the southeast end of the fault in the western Lake Mead region (Duebendorfer, 2003). Most of the fault zone is covered by late Miocene to recent, relatively undeformed sedimentary deposits. The oroclinal flexure is, however, well exposed across much of southern Nevada (Fig. 6), with the Sunrise Mountain area at the north end of the Frenchman Mountain block containing an excellent exposure of the flexure proximal to the projected

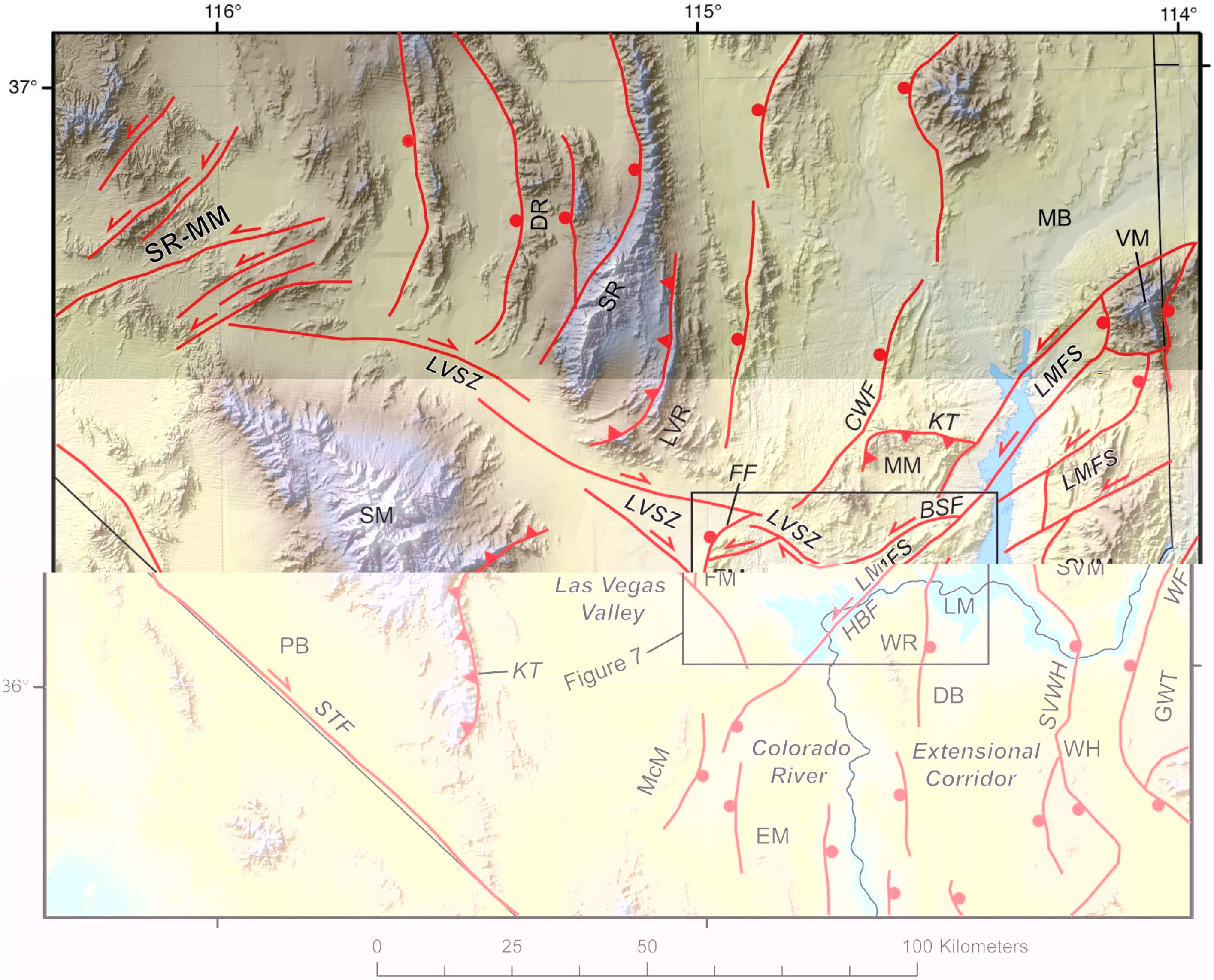

Figure 6. Shaded relief map of major faults and physiographic features in the eastern Walker Lane, including the Las Vegas Valley shear zone (LVSZ), Stateline fault system (STF), Lake Mead fault system (LMFS), and Spotted Range – Mine Mountain domain (SP-MM); data primarily from Stewart and Carlson (1978), Langenheim et al. (2001), Beard et al. (2007), and Guest et al. (2007). Box shows area of Figure 7. For this and following figures, balls shown on downthrown side of faults, arrows indicate sense of strike-slip offset, triangles indicate hanging wall of thrust fault. Major faults (in italics): BSF, Bitter Spring fault; CWF, California Wash fault; FF, Frenchman Mountain fault; HBF, Hamblin Bay fault; KT, Keystone thrust; SVWH, South Virgin – White Hills detachment fault; WF, Wheeler fault. Other features: DB, Detrital basin; DR, Desert Range; FM, Frenchman Mountain; LVR, Las Vegas Range; MB, Mesquite basin; EM, Eldorado Mountains; GWT, Grand Wash trough; LM, Lake Mead; McM, McCullough Mountains; MM, Muddy Mountains; PB, Pahrump basin; SM, Spring Mountains, SR, Sheep Range; SVM, South Virgin Mountains; VM, Virgin Mountains; WH, White Hills; WR, Wilson Ridge.

surface trace of the shear zone. Here, major east-northeast-striking left-lateral faults accommodated much of the flexure and attendant clockwise rotation of fault blocks (Fig. 7). This style of deformation probably dominates along much of the shear zone beneath Las Vegas Valley.

Several features distinguish the Las Vegas Valley shear zone from other parts of the Walker Lane and eastern California shear zone. For example, it trends more northwesterly than other dextral faults. In addition, the >60 km of Neogene dextral offset exceeds that of nearly all other individual faults within the Walker Lane, with the possible exception of the Fish Lake Valley – Furnace Creek – Death Valley fault zone. The temporal evolution of the Las Vegas Valley shear zone also contrasts with other domains in the Walker Lane in that it was active primarily in middle to late Miocene time and has been relatively inactive from late Miocene to recent.

The Stateline fault system is a 200-km-long, northwest-striking (~N45°W) zone of right-lateral faults developed along

[redacted]

valleys. Some of the faults locally cut Quaternary deposits within these valleys. Individual fault lengths range from ~5 to 25 km long. Displacements are 1-2 km or less on individual faults (Carr, 1984). Thus, cumulative left slip is probably minor. Currently, seismological data in the region indicate primarily normal slip, with a small left-lateral component, on active northeast-striking faults (e.g., Meremonte et al., 1995; Smith et al., 2001).

Mojave Desert domain

The Mojave Desert domain (eastern California shear zone of Dokka and Travis, 1990) contains a 150-km-wide belt of dextral shear that links the San Andreas fault system northward to the southern Walker Lane (Death Valley region) and Garlock fault (Figs. 1, 5B, and 8), thus transferring plate margin deformation along the southern San Andreas fault system to the western Great Basin and east of the Sierra Nevada – Great Valley block (Dokka and Travis, 1990; Frankel et al., 2008). Northwest-striking dextral faults dominate most of the domain, but a distinct zone of east-striking sinistral faults occupies the

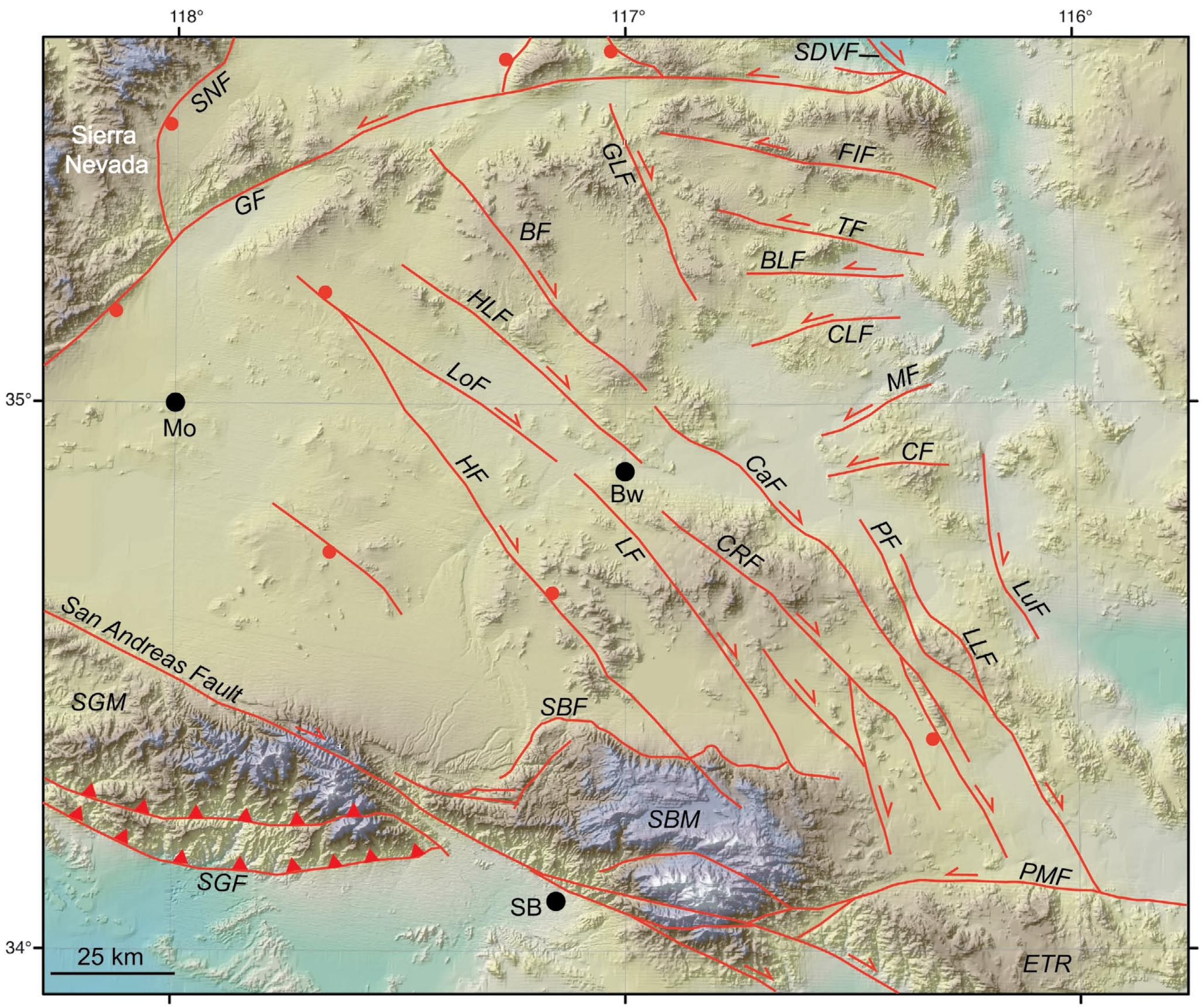

Figure 8. Shaded relief map of major Quaternary faults and physiographic features in the Mojave Desert region of southern California (data from Dokka and Travis, 1990; Frankel et al., 2008). This area essentially encompasses the eastern California shear zone of Dokka and Travis (1990). Major faults (in italics): BF, Blackwater fault; BLF, Bicycle Lake fault; CaF, Calico fault; CF, Cady fault; CLF, Coyote Lake fault; CRF, Camp Rock fault; FIF, Fort Irwin fault; GF, Garlock fault; GLF, Goldstone Lake fault; HF, Helendale fault; HLF, Harper Lake fault; LF, Lenwood fault; LLF, Lavic Lake fault; LoF, Lockhart fault; LuF, Ludlow fault; MF, Manix fault; PF, Pisgah fault; PMF, Pinto Mountain fault; SBF, San Bernardino Mountain fault; SDVF, southern Death Valley fault; SGF, San Gabriel Mountain fault; SNF, Sierra Nevada frontal fault; TF, Tiefort Mountain fault. Other features: Bw, Barstow; Mo, Mojave; ETR, eastern Transverse Ranges; SB, San Bernardino; SBM, San Bernardino Mountains; SGM, San Gabriel Mountains.

northeastern part of the region (Fort Irwin area; Schermer et al., 1996). At least seven major northwest-striking dextral fault zones have been identified in the Mojave Desert domain (Fig. 8). Individual dextral faults range from ~40 to >125 km long, with broad overlap between them and no conspicuous patterns of left- or right-stepping faults. In contrast, the east-striking sinistral faults in the Fort Irwin area vary from ~20 to 40 km in length. Significant clockwise rotation (25°-67°) has accompanied dextral shear in many parts of the Mojave Desert domain, as evidenced by several paleomagnetic studies (e.g., Ross et al., 1989; Ross, 1995; Schermer et al., 1996).

Cumulative dextral shear within the Mojave Desert domain has been estimated at ~65 km since ~13 to 11 Ma (Dokka and Travis, 1990; Schermer et al., 1996). Individual faults have accommodated 0.5 to 21.5 km of right slip, as evidenced primarily by offset early Miocene extensional structures (Dokka, 1983; Dokka and Travis, 1990). Estimates of clockwise rotation (25°-40°) and sinistral shear on the east-striking faults in the Fort Irwin area suggest that half of the dextral shear occurred in the northeast Mojave region (Schermer et al., 1996). Rocks as young as 13 to 11 Ma are as highly deformed as older units, suggesting that strike-slip faulting initiated since 13 to 11 Ma. Middle Pleistocene to locally Holocene rocks are also deformed along many of the strike-slip faults, indicating that significant deformation has continued to the present (Miller et al., 1994; Schermer et al., 1996; Oskin and Iriondo, 2004; Oskin et al., 2006, 2007; Frankel et al., 2008).

Geodetic data indicate contemporary strain rates of 12±2 mm/yr (Savage et al., 1990; Gan et al., 2000; McClusky et al., 2001; Miller et al., 2001; Peltzer et al., 2001). Several faults within this region of dextral shear have recently ruptured in large earthquakes, including the 1992 M_w (moment magnitude) 7.3 Landers and 1999 M_w 7.1 Hector Mine earthquakes. The recent seismic activity is part of a series of $\geq M_w$ 5.0 earthquakes over the past 75 years that defines a N15°W-trending, 120-km-long alignment across the central Mojave region that cuts across older structures and may therefore mark the incipient development of a new through-going fault (e.g., Nur et al., 1993). Paleoseismologic data suggest that these earthquakes are part of an ongoing ≥1000-yr-long seismic cluster (Rockwell et al., 2000). Such clusters appear to characterize earthquake activity over millennial time-scales in the Mojave region (see discussion in Frankel et al., 2008) and may reflect alternating strain accumulation between different components of the southern California fault system (e.g., Mojave Desert vs. Los Angeles regions; Dolan et al., 2007). Accordingly, such rapid strain release evident by the geodetic rates and recent earthquakes is not indicative of longer-term strain rates of ~5-7 mm/yr (Oskin and Iriondo, 2004; Oskin et al., 2006, 2007). However, an intriguing hypothesis is that older faults in the region, including the Big Bend of the San Andreas fault, may be losing their ability to accommodate slip, because they have become unfavorably oriented with respect to the regional stress field (Nur et al., 1993; Du and Aydin, 1996).

Southern Walker Lane

The southern Walker Lane extends from the Garlock fault northward to the Mina deflection (Figs. 1 and 5B). It consists of an ~50-120-km-wide zone of several, variably northwest-striking, broadly overlapping dextral faults partly connected by northeast-striking normal faults and pull-apart basins (Fig. 9). Fault lengths range from ~50 to 250 km. The 250-km-long, N30°-40°W-striking Fish Lake Valley – Furnace Creek – Death Valley fault zone is the longest single fault of the Walker Lane (Reheis and Sawyer, 1997). It extends from the northern end of the White Mountains to Death Valley along or just southwest of the California-Nevada border. Other major dextral faults are the N10°W-striking Saline Valley and Owens Valley – White Mountains faults (Beanland and Clark, 1994; Lee et al., 2001b; Stockli et al., 2003; Glazner et al., 2005; Kylander-Clark et al., 2005). Queen and Deep Springs Valleys are northeast-trending pull-apart basins that transfer slip between the Fish Lake Valley fault zone and faults of Owens Valley (Fig. 9).

Initiation of dextral faulting along the Fish Lake Valley – Furnace Creek – Death Valley fault system at ~10 Ma is well established (Reheis and Sawyer, 1997; Stockli et al., 2003). A sequence of 12-10 Ma basalt and rhyolite flows and an 11.5 Ma, distally sourced ignimbrite were deposited over a low-relief erosional surface that crossed what is now the southern part of the Fish Lake Valley fault zone, which suggests the fault zone did not exist at the time (Reheis and Sawyer, 1997). Fault-related breccia and alluvial fan deposits are as old as 8.2 Ma (Reheis and Sawyer, 1997). The Fish Lake Valley – Furnace Creek – Death Valley fault system accommodated most of the displacement in the southern Walker Lane before ~6 Ma.

Strike-slip faulting migrated westward to the White Mountains and Owens Valley faults along several northeast-striking normal faults beginning ~3 Ma (Stewart, 1988; Reheis and Dixon, 1996; Stockli et al., 2003). As this occurred, rates of displacement diminished from 6-16 mm/yr before ~6 Ma to 1-3 mm/yr after ~2 Ma on the Fish Lake Valley – Furnace Creek – Death Valley fault system (Reheis and Sawyer, 1997). Migration began ~3 Ma with displacement on the Queen Valley fault and development of a pull-apart basin at the north end of the White Mountains (Fig. 9; Stockli et al., 2003). Transfer across Queen Valley facilitated the transition of the White Mountains fault from a normal system that accommodated 8 km of down-to-the-west displacement beginning ~12 Ma (as part of the pre-strike-slip east-west extension) to a right-oblique fault (Stockli et al., 2003). The Deep Springs fault and Deep Springs Valley comprise a northeast-striking normal fault and pull-apart basin between the White and Inyo Mountains that became active about 1.7 Ma and transfer a substantial amount of slip from the Fish Lake Valley fault to the Owens Valley fault (Lee et al., 2001a).

Owens Valley is distinctive in the Walker Lane – eastern California shear zone in having a complex system of parallel

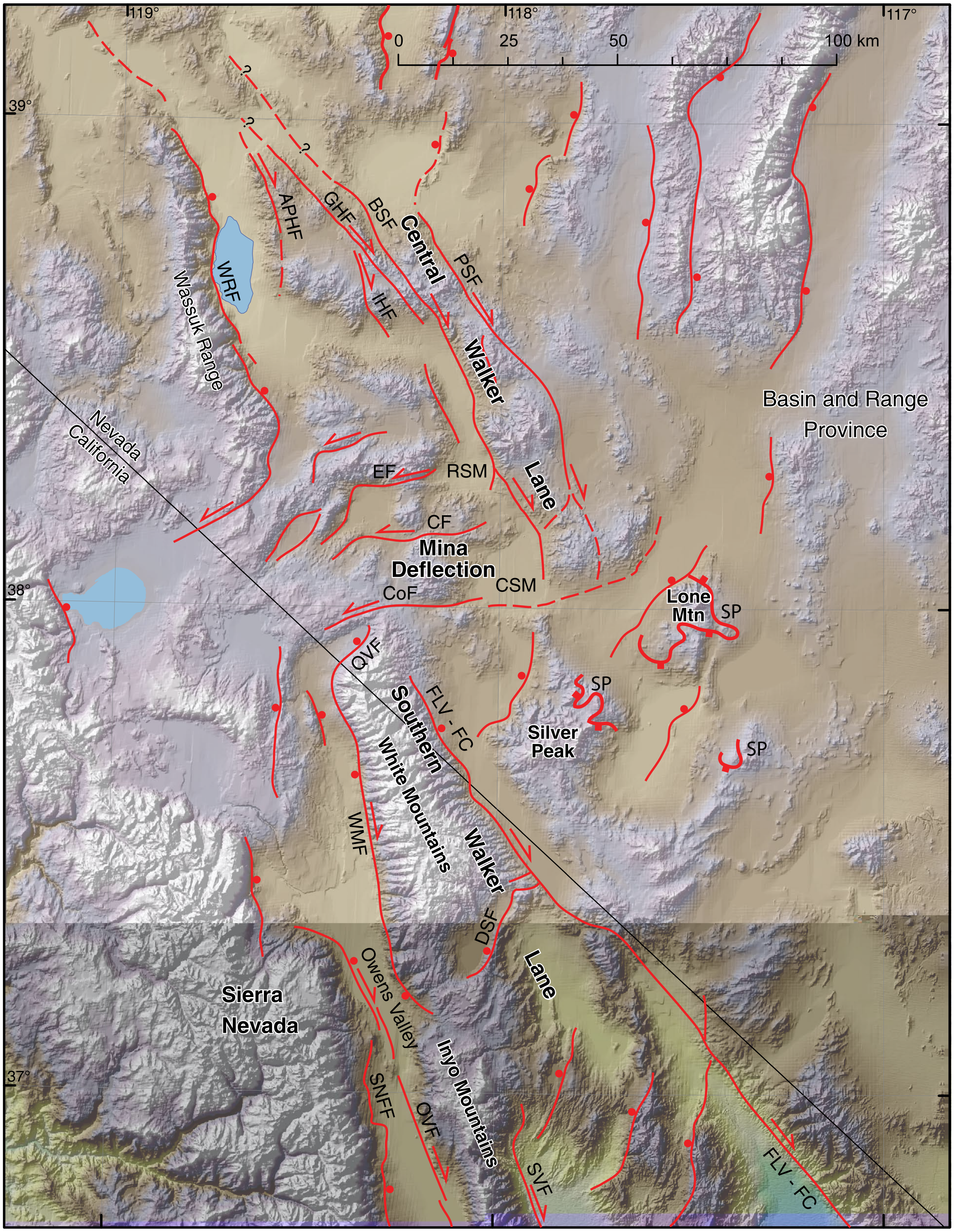

Figure 9. Shaded relief map of major faults and physiographic features of the southern and central Walker Lane and their connection through the Mina deflection; also shows selected faults of the adjacent Basin and Range (from Ekren and Byers, 1984; Hardyman, 1984; Stewart, 1988; Oldow, 1992; Wesnousky, 2005a). Walker Lane faults: APHF, Agai Pai Hills fault; BSF, Benton Spring fault; CF, Candelaria fault; CoF, Coaldale fault; DSF, Deep Springs Valley fault; EF, Excelsior fault; FLV-FC, Fish Lake Valley – Furnace Creek fault; GHF, Gumdrop Hills fault; IHF, Indian Head fault; OVF, Owens Valley fault; PSF, Petrified Spring fault; QVF, Queen Valley fault; SP, Silver Peak – Lone Mountain detachment fault (with squares on upper plate); SVF, Saline Valley fault; WMF, White Mountains fault. Other features: CSM, Columbus Salt Marsh; RSM, Rhodes Salt Marsh; SNFF, Sierra Nevada frontal fault; WRF, Wassuk Range frontal fault.

and contemporaneously active dextral, normal, and oblique-slip faults (Fig. 9). These are the N10°-20°W-striking, dextral Owens Valley fault, the normal-displacement Sierra Nevada frontal fault system, which lies 2 to 15 km to the west, and the right-oblique White – Inyo Mountains fault zones, which lie 5 to 10 km to the east (Beanland and Clark, 1994). All faults have accommodated Holocene slip (Beanland and Clark, 1994; Lee et al., 2001b; Bacon and Jayko, 2004; Le et al., 2007). The Owens Valley faults strike much more northerly than other Walker Lane faults (e.g., the Fish Lake Valley fault) and strongly oblique to the ~N47°W transport direction of the Sierra Nevada block relative to the Colorado Plateau (Dixon et al., 2000; Unruh et al., 2003). Henry et al. (2007) suggested that this oblique orientation required partitioning of strain into the three fault sets. The Owens Valley fault ruptured in 1872 in a M_w 7.6 earthquake, which produced dextral offset averaging ~6 m along a 100 km length (Beanland and Clark, 1994).

Cumulative right slip across the southern Walker Lane is roughly constrained between ~40 and 110 km. Estimates of total slip on the Fish Lake Valley – Furnace Creek – Death Valley fault system range from 30 to 100 km based on offsets of stratigraphic markers and isopach trends (Stewart, 1967, 1988; McKee, 1968; Reheis and Sawyer, 1997), but Reheis and Sawyer (1997) favored 40-50 km based on offset of a Jurassic quartz monzonite (McKee, 1968). Consistent with its late development, the Owens Valley fault has accommodated no more than ~10 km of dextral displacement in the late Cenozoic (Lee et al., 2001b), although Beanland and Clark (1994) suggested possibly up to 20 km. Glazner et al. (2005) and Kylander-Clark et al. (2005) summarized evidence for 65 km of total right-lateral slip across Owens Valley but concluded that most of this slip occurred in the Late Cretaceous along a fault that was reactivated in the late Cenozoic as the Owens Valley fault. GPS data indicate >10 mm/yr of dextral shear across the southern Walker Lane (Dixon et al., 1995; Gan et al., 2000). Paleomagnetic data indicate that the Black Mountain fault block in the Death Valley area has undergone as much as 50°-80° of clockwise rotation (Holm et al., 1993). Vertical axis rotations have not been investigated in most other parts of the southern Walker Lane but are probably minor.

Central Walker Lane

Mina deflection. The southern Walker Lane steps nearly 60 km eastward to the central Walker Lane across the east-northeast-trending Excelsior-Coaldale block or Mina deflection (Stewart, 1988; Oldow, 1992) (Figs. 5B and 9). The origin and significance of this block, especially the influence of pre-Cenozoic structures, have been interpreted in numerous ways (Stewart, 1988, 1992). The Mina deflection is now generally interpreted to transfer slip from the northwest-striking dextral faults of the southern Walker Lane to similar faults of the central Walker Lane (Oldow, 1992; Oldow et al., 1994; Bradley et al., 2003; Tincher and a ,
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Hardyman et al. (2000) increased this estimate to at least 60 to 78 km. However, it is important to note that the western faults in this system only overlap partially with the eastern faults. Thus, cumulative dextral slip along any single profile orthogonal to the fault system in the central Walker Lane may be closer to ~40 km (Fig. 9).

Strike-slip faulting in the central Walker Lane has been interpreted to have begun in the late Oligocene but clearly became active by ~10 Ma. On the basis of apparent angular unconformities between Oligocene to lower Miocene ash-flow tuffs, paleosurfaces with major topography, deposition of tuffs of different ages on basement, and intrusion of late Oligocene dikes along northwest-striking faults, Hardyman (1980), Ekren et al. (1980), and Dilles and Gans (1995) inferred that Cenozoic strike-slip faulting began ~25 Ma in the central Walker Lane. However, Henry et al. (2003), Eckberg et al. (2005), and Henry and Faulds (in prep.) surmised that these relationships mostly reflect deposition of the tuffs in paleovalleys (e.g., Proffett and Proffett, 1976; Faulds et al., 2005a). Hardyman and Oldow (1991) suggested that the late Oligocene – early Miocene faulting may have been dominantly extensional or even sinistral and that right-lateral faulting probably began by ~10 Ma, consistent with the initiation of faulting in the southern Walker Lane. Hardyman and Oldow (1991) based this interpretation on deposition of 13 to 8 Ma syntectonic sedimentary rocks in fault-bound basins and displacement of the same rocks by northwest-striking dextral faults. Thermochronologic data indicate that the Wassuk Range frontal fault has undergone only normal displacement beginning at ~15 Ma and continuing to the present (Stockli et al., 2002; Surpless et al., 2002; Wesnousky, 2005a), which places both a spatial and temporal limit on the Walker Lane at this latitude. This range-front fault strikes slightly more northerly than the dextral faults and is similar in setting to the Sierra Nevada frontal fault in the southern Walker Lane.

The central Walker Lane has continued to accommodate dextral shear through the Quaternary. All dextral faults within the region have Quaternary scarps, with the youngest recognized surface-rupturing event occurring 800 years ago on the Benton Spring fault (Wesnousky, 2005a). Wesnousky (2005a) concluded that most of the present-day dextral slip is accommodated by the Benton Spring and Petrified Spring faults. GPS geodetic data indicate ~10 mm/yr of dextral shear currently across the region (Oldow et al., 2001; Bennett et al., 2003).

Several north-northeast-striking normal faults splay off the northeastern flank of the central Walker Lane and transfer slip into the seismically active central Nevada seismic belt (Fig. 9; e.g., Caskey et al., 2001, 2004; Bell et al., 2004). These faults could allow migration of dextral faulting northeast of the current Walker Lane, similar to the westward migration of dextral faulting in the southern Walker Lane, but this has not yet occurred.

Northern Walker Lane

The northern Walker Lane extends northwestward from the central Walker Lane and consists of three distinct domains (Figs. 1, 5B, and 10). The Carson and Pyramid Lake domains of Stewart (1988) lie primarily in western Nevada, whereas the Modoc Plateau domain occupies a broad region of northeast California. The Modoc Plateau domain represents the northwestern terminus of the Walker Lane – eastern California shear zone. Northwest-striking dextral faults dominate the Pyramid Lake and Modoc Plateau regions, in contrast to the prevailing east- to northeast-striking sinistral faults in the Carson domain. The onset of strike-slip faulting may have propagated northwestward in the northern Walker Lane, beginning as early as 9 Ma in the Carson domain and as late as ~4-3 Ma in the Pyramid Lake and Modoc Plateau domains (see discussion below). Thus, much of the northern Walker Lane may be the youngest part of the Walker Lane – eastern California shear zone.

Carson domain. The Carson domain is an ~80-km-wide region of east- to northeast-striking fault zones (Stewart, 1988) and clockwise-rotated fault blocks (Cashman and Fontaine, 2000; Faulds and Perkins, 2007) sandwiched between discrete northwest-striking dextral fault systems in the Walker Lake and Pyramid Lake domains (Figs. 1, 5B, and 10). Three major zones of east-northeast- to northeast-striking faults, ranging from ~25 to 100 km long, have been recognized in the Carson domain. From south to north, these are the Wabuska lineament, Carson lineament, and Olinghouse fault zone (Fig. 10). Only the Olinghouse fault has been studied in any detail. Structural analyses indicate as much as 3 km of sinistral slip along this fault zone, with lesser amounts of normal offset (Sturmer, 2007; Sturmer et al., 2007). The Olinghouse fault has ruptured in the Holocene (Briggs and Wesnousky, 2005) and may have generated a M_w 7 earthquake in the 1860s (Sanders and Slemmons, 1979). In a paleomagnetic study, Cashman and Fontaine (2000) documented 35°-44° of clockwise rotation of fault blocks in the central part of the Carson domain. However, more recent geologic mapping and paleomagnetic investigations have documented a large oroclinal flexure in the eastern part of the domain (Fig. 10), with more than 90° of clockwise rotation of fault blocks (Faulds and Ramelli, 2005; Faulds and Perkins, 2007). The rotated blocks documented by Cashman and Fontaine (2000) occupy the western part of this oroclinal flexure. The flexure suggests a minimum of ~30 km of dextral shear across the eastern Carson domain. Unlike the Las Vegas Valley shear zone, however, the oroclinal flexure in this region may not be breached by a major right-lateral fault. GPS geodetic strain rates of ~10 mm/yr across the region (Kreemer et al., in press) indicate ongoing dextral shear across the oroclinal flexure in the eastern Carson domain. The onset of dextral shear within the Carson domain is bracketed between ~9 and 5 Ma. About 25° of the clockwise vertical-axis rotation within the western Carson domain is constrained between ~9 and 5 Ma (Cashman and Fontaine, 2000), and

>90° of clockwise rotation in the eastern Carson domain has occurred since ~6 Ma (Faulds and Perkins, 2007; Faulds and Henry, unpublished data).

Pyramid Lake domain. The 45-80-km-wide Pyramid Lake domain is dominated by a left-stepping en echelon system of right-lateral faults ranging from ~50 to 100 km in length (Figs. 1, 5B, and 10; Stewart, 1988; Faulds et al., 2005a, b; Henry et al., 2004, 2007; Hinz et al., in press). From east to west, major dextral faults are the Pyramid Lake, Warm Springs Valley, Honey Lake, Grizzly Valley, and Mohawk Valley faults (Fig. 10). The dextral faults in the Pyramid Lake domain are kinematically linked to systems of north- to north-northeast-striking normal faults. In the west, major dextral faults merge southward with a system of east-dipping normal faults, which coalesce southward to form the Sierra Nevada frontal fault system. To the east, the Pyramid Lake fault splays northward into a system of west-dipping normal faults (Faulds et al., 2005b; Drakos, 2007). All dextral faults in the Pyramid Lake domain have Quaternary fault scarps and most have ruptured at least once in Holocene time (e.g., Wills and Borchardt, 1993; Adams et al., 2001; Briggs and Wesnousky, 2004; dePolo et al., 2005). Paleomagnetic data

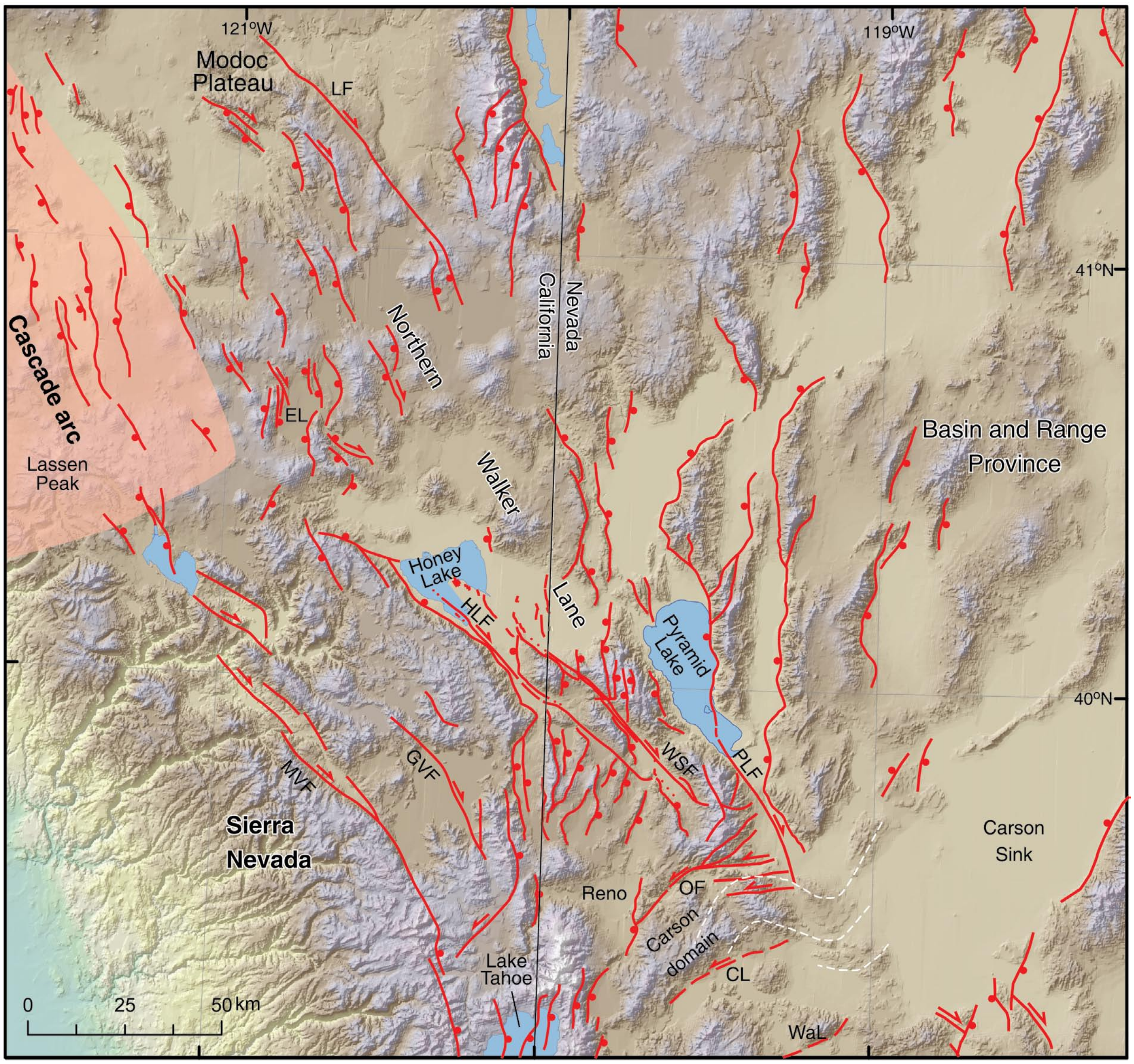

Figure 10. Shaded relief map of major faults and physiographic features of the northern Walker Lane (Carson, Pyramid Lake, and Modoc Plateau domains); also shows selected faults of the adjacent Basin and Range Province and Cascade volcanic arc (from Gay and Aune, 1958; Lydon et al., 1960; Bonham and Papke, 1969; Stewart, 1988; Saucedo and Wagner, 1992; Grose, 2000; Henry et al., 2007). White dashed lines denote orocline in the eastern part of the Carson domain. CL, Carson lineament; EL, Eagle Lake; GVF; Grizzly Valley fault; HLF, Honey Lake fault; LF, Likely fault; MVF, Mohawk Valley fault; OF, Olinghouse fault; PLF, Pyramid Lake fault; WaL, Wabuska lineament; WSF, Warm Springs Valley fault. In the Modoc Plateau domain, dextral displacement is generally not well constrained but is documented on a fault at Eagle Lake (Colie et al., 2002) and inferred for several other faults (e.g., Grose, 2000; Poland et al., 2002).

indicate slight (~15°-25°) counterclockwise rotation in much of the Pyramid Lake domain (Cashman and Fontaine, 2000; Faulds et al., 2004b) in contrast to the large clockwise rotations to the south in the eastern Carson domain. Offset, tuff-filled Oligocene paleovalleys suggest that the Pyramid Lake, Warm Springs Valley, and Honey Lake faults have each accommodated ~10 km of dextral slip (Faulds et al., 2005a, b; Hinz et al., in press). Dextral offset appears to be minimal (<~2 km) along the Grizzly Valley and Mohawk Valley faults. Thus, cumulative dextral offset across the overlapping en echelon dextral faults is ~20-25 km along a northeast-trending profile oriented approximately orthogonal to the Walker Lane. GPS geodetic data indicate northwest-directed dextral shear rates of ~10 mm/yr across the Pyramid Lake domain (Hammond and Thatcher, 2004, 2007; Kreemer et al., in press).

Several relationships suggest a relatively recent onset of strike-slip deformation in the Pyramid Lake domain. For example, tilts are generally concordant between middle Miocene volcanic rocks and Oligocene tuffs, suggesting that no appreciable deformation accompanied Oligocene through middle Miocene magmatism. Northwest-striking ~22 Ma veins in the Pah Rah Range, previously attributed to early Walker Lane deformation (Wallace, 1975), probably record minor northeast-southwest extension, an unlikely consequence of northwest-trending dextral shear (Faulds et al., 2005c). Although ~east-west extension initiated basin development ~13 Ma in the region (Trexler et al., 2000), there is no evidence that strike-slip faulting accompanied early stages of Miocene extension. Moreover, 3.5 Ma sediments along the Warm Springs Valley fault are as highly deformed as Oligocene tuffs (Henry et al., 2007). Considering these relations, we infer that most of the right-lateral faulting within the Pyramid Lake domain has occurred since ~3.5 Ma. Recent movement on strike-slip and normal faults has been broadly coeval, as evidenced by Quaternary fault scarps and historical seismicity (e.g., Bell, 1984; dePolo et al., 1997; Ichinose et al., 1998). The inferred magnitude (20-30 km of dextral slip across the northern Walker Lane) and timing of deformation suggest long-term slip rates of ~2-10 mm/yr, which is compatible with geodetic data from the region (e.g., Bennett et al., 2003; Hammond and Thatcher, 2004).

Modoc Plateau domain. The discrete belt of dextral faults in the Pyramid Lake domain gives way northwestward in the Modoc Plateau region of northeast California to a diffuse ~80 km wide zone of widely spaced northwest-striking faults and lineaments that extend northwestward to the southern Cascade arc (Figs. 1, 5B, and 10; Pease, 1969; Page et al., 1993; Grose, 2000; Colie et al., 2002). These faults cut across a relatively young landscape largely covered by late Miocene to recent mafic lavas and punctuated by numerous shield volcanoes and cinder cones (Fig. 10). Most of the faults have relatively short strike lengths (<50 km) and definite normal separation, but only a few faults have been sufficiently studied to demonstrate dextral slip, which is minimal (<<1 km). The Likely fault is one of the more continuous faults in the region with a length of ~64 km, but evidence for significant dextral displacement along the fault has not been observed (Bryant, 1991). GPS geodetic data suggest ~2.5 mm/yr of dextral shear across northeast California (Poland et al., 2006), and fault studies suggest low rates of deformation (Bryant and Wills, 1991). Major northwest-striking dextral faults have not been observed either within or directly west of the southern Cascade arc. Thus, the Walker Lane appears to terminate northwestward in northeast California and southernmost Oregon. Although the timing of deformation is not well constrained in the Modoc Plateau domain, we infer that strike-slip faulting initiated since ~3.5 Ma on the basis of constraints in the adjacent Pyramid Lake domain and the fact that strike-slip faults in the Modoc Plateau region cut late Miocene to Quaternary mafic lavas.

DISCUSSION

In this section, we first summarize the spatial and temporal evolution of the Walker Lane – eastern California shear zone by reviewing data from the various structural domains (Table 1). A kinematic model is proposed that incorporates the spatial and temporal constraints, as well as the overall geometric patterns of faulting throughout the shear zone. The influences of major plate boundary events on the overall kinematic evolution of the Walker Lane – eastern California shear zone are then assessed. We propose a possible future for the Walker Lane – eastern California shear zone based on its known evolution and reasonable extrapolation of triple junction migration. Finally, we discuss the potential broader implications of these findings on tectonic processes.

Spatial and temporal constraints

A review of salient features of the various domains within the Walker Lane – eastern California shear zone (Table 1) reveals several important patterns in the spatial and temporal evolution of the system. One of the most conspicuous features is the earlier episode of deformation within the eastern Walker Lane of southern Nevada (e.g., Las Vegas Valley shear zone; Figs. 2 and 6), as this area accommodated dextral shear primarily between 13 and 6 Ma. Approximately 60 km of dextral shear was largely accommodated in ~7 Ma along the N60°W-trending Las Vegas Valley shear zone, suggesting long term strain rates of ~8-9 mm/yr. Cumulative dextral shear (~60 km) along the Las Vegas Valley shear zone may be the largest magnitude offset on any single fault within the Walker Lane, with only the Fish Lake Valley – Furnace Creek – Death Valley fault system as a possible rival. However, sparse Quaternary fault scarps, minor historic seismicity, and minimal geodetic strain rates all suggest that this region is currently accommodating little, if any, of the relative motion between the Pacific and North American plates. Thus, activity in the eastern Walker Lane appears to have peaked in the middle to late Miocene and waned significantly since ~6 Ma.

In contrast, the bulk of the Walker Lane – eastern California shear zone to the west (Figs. 1 and 5B), within the western Great Basin, has been most active since late Miocene to recent time (Table 1). Although not tightly constrained in some domains, dextral faulting began ~11 to 9 Ma in most areas and possibly as young as 4 to 3 Ma in the northernmost reaches (e.g., Pyramid Lake and Modoc Plateau domains). Abundant Quaternary fault scarps, significant recent seismicity, and appreciable geodetic strain rates (averaging ~10 mm/yr of northwest directed dextral shear) indicate that the entire region from the Mojave Desert domain on the south to the Modoc Plateau domain on the north is currently functioning as an integral part of the Pacific – North American plate boundary. Presently active parts of the Walker Lane in the western Great Basin generally trend more northerly (~N20°-45°W) than the N60°W-trending Las Vegas Valley shear zone (Figs. 1, 6, and 9). Estimates of dextral offset in the western Great Basin vary between individual domains, but ~60 km represents an approximate overall average. This suggests long-term strain rates of ~6 mm/yr over the 10 Ma long life span of most segments, somewhat lower than the current GPS geodetic rates. This discrepancy may simply reflect lower strain rates during initial development of the system (ca. 10 Ma) and more recent rapid rates as the system has matured and become better organized.

The broad fault patterns within the domains of the Walker Lane can be viewed as a general hierarchy in terms of stages of evolution. Considering proximity to the San Andreas fault system, a general younging and decrease in organization might be expected from south to north within the shear zone. However, most of the Walker Lane – eastern California shear zone, from the Mojave Desert domain through the central Walker Lane, appears to have initiated at indistinguishably the same time ~11 Ma. Also, the southern Walker Lane, approximately in the middle of the overall Walker Lane – eastern California shear zone, appears to be the most highly evolved and best developed part of the system, as evidenced by greater fault lengths, broad overlap between major faults, and the potentially largest magnitude of offset (Fig. 9, Table 1). The 250-km-long Fish Lake Valley – Furnace Creek – Death Valley fault system (McKee, 1968; Reheis and Sawyer, 1997) is the longest within the entire Walker Lane – eastern California shear zone and may have also accommodated the greatest amount of offset (30-100 km) within the system. North of the Mina deflection, left-stepping en echelon 12-100 km long faults, commonly with minimal overlap and each with only 1-16 km of offset, characterize the dextral fault systems in the central and northern Walker Lane (Hardyman, 1984; Ekren and Byers, 1984; Faulds et al., 2005a). South of the Garlock fault, 40-125 km long, significantly overlapping dextral faults, with less than 22 km of slip on each, dissect the Mojave Desert domain (Fig. 8; Dokka, 1983; Dokka and Travis, 1990). Thus, on the basis of fault lengths and inferred magnitude of offset, the southern Walker Lane appears to be the most highly evolved part of the active Walker Lane – eastern California shear zone.

On the other hand, the northwestern part of the Walker Lane in northwest Nevada and northeast California is probably the least evolved and possibly youngest part of the system. Dextral faults in the Pyramid Lake domain have a maximum offset of ~10 km (Faulds et al., 2005a) and may be younger than ~3.5 Ma (Henry et al., 2007). The left-stepping pattern of dextral faults in both the Pyramid Lake and Walker Lake domains (Figs. 9 and 10) epitomizes the incipient nature of northern parts of the system, as these may be analogous to macroscopic Riedel shears (cf., Petit, 1987) devel

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Evidence for this earlier stage abounds in northwest Nevada, as blocks between major strike-slip faults commonly contain minor inactive northwest-striking dextral faults (Faulds et al., 2003, 2005a).

The slight counterclockwise rotation in the Pyramid Lake domain is opposite the typical clockwise rotation observed in most other parts of the Walker Lane – eastern California shear zone (e.g., Table 1; Nelson and Jones, 1987; Sonder et al., 1994; Ross, 1995; Schermer et al., 1996). In the transtensional setting of the northern Walker Lane, coeval dextral shear in the left-stepping fault system, west-northwest regional extension, and a lesser component of north-south shortening may account for the counterintuitive counterclockwise rotation (Faulds et al., 2005a; Fig. 11). This sense of rotation would ultimately rotate Riedel shears toward the orientation of the main shear zone at depth, thus facilitating eventual development of a through-going, upper-crustal strike-slip fault. Ironically, as such a fault develops and the strike-slip fault system matures, the sense of vertical-axis rotation may reverse and become compatible with the overall shear strain. The apparent change from counterclockwise to clockwise rotations southeastward in the Walker Lane (e.g., Pyramid Lake vs. Carson domains; Cashman and Fontaine, 2000; Faulds et al., 2004b) may reflect such a progression. Such complex kinematics may characterize the early evolution of major strike-slip fault systems.

Thus, the active portions of the Walker Lane – eastern California shear zone in the western Great Basin may record several stages in the evolution of an intracontinental strike-slip fault system (Table 1). Stage one comprises a broad zone of widely spaced Riedel shears in northeast California. Stage two, in northwest to west-central Nevada (Figs. 9 and 10), consists of a narrower belt of overlapping Riedel shears, which may indicate a through-going dextral shear zone in the upper mantle and/or lower crust (Faulds et al., 2005a). Both the Pyramid Lake and Walker Lake domains (Fig. 5B) would represent stage two. However, greater amounts of both overlap and apparent offset of dextral faults suggest that the Walker Lake domain is at a slightly more advanced stage compared to the Pyramid Lake domain. The southern Walker Lane may reflect a third stage of development in which many of the early en echelon Riedel shears have rotated into more favorable orientations to become through-going structures, as exemplified by the Fish Lake Valley – Furnace Creek – Death Valley fault system (Fig. 9). Although relatively inactive today, the Las Vegas Valley shear zone may also record a stage three level of development during the middle to late Miocene event. Where the Mojave Desert domain fits within this hierarchy is questionable. It resembles the broader more diffuse pattern of faulting that characterizes the Modoc Plateau, but it also contains many relatively long faults, some of which have accommodated ~20 km of right slip. We therefore suggest that the Mojave region is at a relatively advanced stage of development, but critical boundary conditions (e.g., proximity to the San Andreas fault system) have precluded more focused deformation (as discussed below). It is important to note, however, that preexisting structures in continental lithosphere may greatly influence patterns of strain, thus precluding the straight-forward progressive development of regional fault systems. The apparent earlier history of the Owens Valley fault zone and its recent reactivation as part of the southern Walker Lane (e.g., Glazner et al., 2005) may be a good example of this.

Kinematic role of sinistral fault domains

Another important question concerns the kinematic role of the domains of east- to northeast-striking sinistral faults, including the Lake Mead, Spotted Range-Mine Mountain, Mina deflection, and Carson domains (Fig. 1 and 5). Deformation in all of these domains was coeval with dextral shear in adjacent regions (Table 1), and most of these domains have experienced significant components of clockwise vertical-axis rotation (Cashman and Fontaine, 2000; Wawrzyniec et al., 2001; Petronis et al., 2007; Faulds and Perkins, 2007), compatible with regional dextral shear. Cashman and Fontaine (2000) invoked a model in which northeast-striking sinistral faults in the Carson domain accommodate the clockwise rotation of fault blocks and thereby facilitate regional dextral shear. More recent work has shown that the rotated fault blocks in this region are part of a large oroclinal flexure, with as much as 90°-100° of clockwise rotation (Fig. 10; Faulds and Perkins, 2007). The northeast- to east-striking sinistral faults in this region accommodated developmise ro p
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clockwise rotation (Petronis et al., 2007), these studies were conducted primarily to the south of the main active part of the Mina deflection. Thus, more paleomagnetic work is needed to fully resolve the kinematics of the Mina deflection.

It is noteworthy, however, that nearly all of the domains of east- to northeast-striking sinistral faults are associated with preexisting structures. For example, the Neoproterozoic cratonic rift margin trends east-northeast near the Mina deflection, as marked by the $^{87}Sr/^{86}Sr_i$ 0.706 line (Fig. 1; Wetterauer, 1977; Stewart, 1988). The Lake Mead fault system may also be controlled by an ancient east- to northeast-trending crustal flaw, as it marks the northward terminations of an early Tertiary arch, early to middle Miocene volcanic terrane, and middle to late Miocene northern Colorado River extensional corridor (Fig. 6). Even the petrogenesis of late Miocene lavas differs across the Lake Mead fault system, with an asthenospheric contribution to the south but only a mantle lithospheric component to the north (Feuerbach et al., 1993). Thus, the Lake Mead domain may represent a fundamental lithospheric boundary that has partitioned strain and magmatism for at least the past 75 Ma, possibly originating as part of a discontinuity or transfer zone during Late Proterozoic extension (Faulds et al., 2001). The Carson domain is part of the Humboldt structural zone (Rowan and Wetlaufer, 1981), a broad belt of east-northeast-striking faults and high heat flow that extends across much of northern Nevada and is on trend with major structures in southeast Idaho (Lageson and Faulds, 1999), suggesting that it also follows a major preexisting crustal weakness. We therefore suggest that the domains of east- to northeast-striking faults within the Walker Lane – eastern California shear zone were partly to largely controlled by major preexisting discontinuities oriented oblique to nearly orthogonal with the main northwest-trending belt of dextral shear.

Intracontinental accommodation of dextral shear

As an intracontinental manifestation of plate boundary strain, dextral shear at the terminus of the Walker Lane – eastern California shear zone must be accommodated by deformation within western North America. So where does this dextral shear go? We suggest that most of this shear strain has been and continues to be transferred into west-northwest extension within the Basin and Range province (Fig. 12).

A broad review of slip magnitude and strain rates within the Walker Lane – eastern California shear zone (Table 1) shows that cumulative slip decreases from ~60 km or more in southern reaches, to 20-30 km in the northern Walker Lane, and to essentially zero in northeastern California concomitant with a decline in current strain rates from ~10 mm/yr to negligible (e.g., Oldow et al., 2001; Blewitt et al., 2003; Bennett et al., 2003; Faulds et al., 2005a; Hammond and Thatcher, 2004, 2005, 2007; Poland et al., 2006; Kreemer et al., in press). Accordingly, dextral motion across the Walker Lane essentially terminates in northern California. Thd M

sl M wd wd d l rm strd d heiacm northe t northwestern Great Basin is situated in a youthful transtensional setting that accommodates a northward decrease in dextral shear in the evolving transform boundary between the North American and Pacific plates. Enhanced extension favors dilation and deep circulation of aqueous solutions along north-northeast-striking faults and probably accounts for the abundant geothermal activity in this region (Faulds et al., 2004a). The apparent northward diffusion of much of the dextral shear along both the Las Vegas Valley shear zone (Fig. 6; e.g., Guth, 1981) and Walker Lake domain (Fig. 9; e.g., Oldow, 1992; Oldow et al., 1994, 2001) is broadly similar to the contemporary pattern of faulting in the northern Walker Lane (Fig. 10). Thus, diffusion of dextral shear into Basin and Range extension has probably been an ongoing process throughout the history of the Walker Lane – eastern California shear zone since its inception in southern Nevada ~13 Ma.

These relations further suggest that the Sierra Nevada block and northwesternmost Great Basin are essentially one micro-plate and that the Sierra Nevada has been progressively decoupling from the Great Basin as the Walker Lane has evolved since the late Miocene (Fig. 12). Initial northwestward movement of the Sierra Nevada block has been estimated at ~8 Ma (Wernicke and Snow, 1998), which is compatible with the inferred onset of dextral shear at ~10 Ma within the southern and central parts of the Walker Lane. To the north, movement of this block is currently accommodated by the clockwise rotation of western Oregon and a belt of north-south shortening in western Washington (Fig. 3; Wells et al., 1998; Miller and Johnson, 2002; Svarc et al., 2002), suggesting a pole of rotation in north-central Idaho (e.g., Jones and Oldow, 2004).

It is intriguing that significant (~55 km) middle to late Miocene north-south shortening also occurred in the Lake Mead region essentially coincidental with the main episode of movement on the Las Vegas Valley shear zone (e.g., Anderson et al., 1994; Duebendorfer and Simpson, 1994). Similar to the current north-south shortening in western Washington, which accommodates the northwestward translation of the Sierra Nevada block, the earlier episode of north-south shortening in the Lake Mead region may have accommodated part of the relative dextral translation across the Walker Lane. This strain may have been focused in the Lake Mead region as more mobile crust along the Las Vegas Valley shear zone encountered and essentially collided with relatively in situ crust to the east, thereby generating a locus of deformation involving coeval oroclinal flexure, clockwise rotation, northwest-striking dextral faults, northeast-striking left-lateral faults, east-trending folds, and northerly striking normal faults. Accommodation of dextral shear by extension toward the west end of the Las Vegas Valley shear zone (Guth, 1981) versus a component of north-south shortening at the east end (Anderson et al., 1994) is attributed to the stable cratonic abutment on the east in contrast to more mobile Cordilleran crust (on the west) that could extend westward by either over-riding the subduction zone or inducing shortening along the San Andreas fault system.

It is notable that major east-west extension directly south of Lake Mead in the Colorado River extensional corridor ended relatively abruptly ~13 Ma (Faulds et al., 2001) approximately coincidental with the onset of dextral shear along the Las Vegas Valley shear zone and development of the complex strain field in the Lake Mead region. This marked the end of an early to middle Miocene episode of northward propagating, large-magnitude ~east-west extension in the Colorado River extensional corridor (Faulds et al., 1999). Past models have suggested a link between major east-west extension in the Colorado River corridor and transform-like motion on the Las Vegas Valley and Lake Mead shear zones (e.g., Liggett and Childs, 1977). However, consideration of the relative timing of deformation in the context of plate boundary evolution implies that the converse may be more plausible, whereby initiation of the Walker Lane and dextral shear along the Las Vegas Valley shear zone effectively terminated the northward propagating rift within the extensional corridor. These relations suggest that the early manifestation of the inboard, plate boundary dextral motions had a profound and complex effect on spatial and temporal patterns of deformation within neighboring parts of the Basin and Range province.

Summary of kinematic evolution

A review of the spatial and temporal constraints for the various domains within the Walker Lane – eastern California shear zone permits modeling of the general kinematic evolution of the shear zone. The first major episode of deformation affected the eastern Walker Lane, which began developing in the middle Miocene ~13 Ma. The N60°W Las Vegas Valley shear zone was the locus of deformation in this region, accommodating ~60 km of right slip from ~13 to 6 Ma. A complex middle to late Miocene strain field in the Lake Mead region, which included significant (~55 km) north-south shortening and northeast-striking sinistral faults, may have resulted from the displacement and collision of more mobile parts of the western Cordillera (e.g., block on north side of Las Vegas shear zone) against relatively in situ parts of the North American craton to the east.

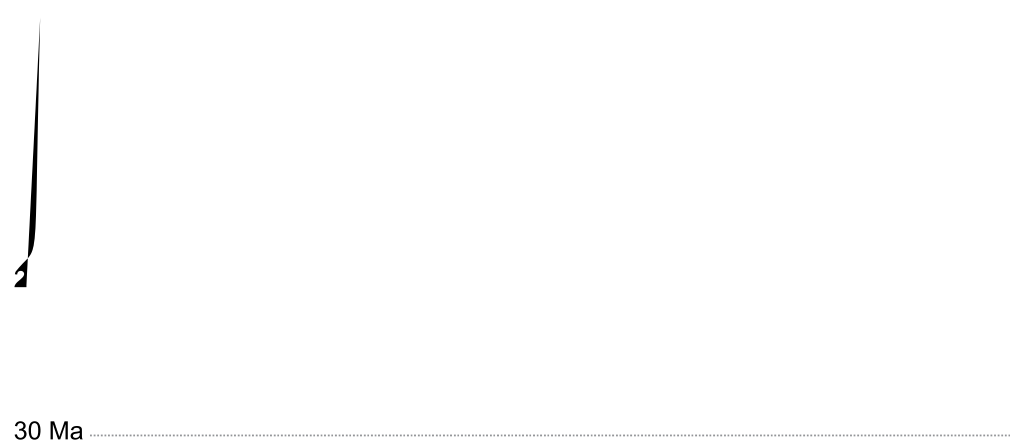
Between ~11 and 6 Ma, the principal locus of dextral shear shifted westward to a N20°W-N45°W-trending belt in the western Great Basin, although minor activity has continued into the Quaternary within the eastern Walker Lane. Dextral shear within the Mojave Desert domain, southern Walker Lane, and central Walker Lane all began ~10-11 Ma. On the basis of fault lengths, the southern Walker Lane appears to be the most structurally evolved part of the late Miocene to recent portion of the shear zone in the western Great Basin. This could indicate that dextral shear within the western Great Basin began in the southern Walker Lane and then propagated relatively rapidly to both the north and south in late Miocene time. However, faulting began in the Mojave Desert domain at indistinguishably the same time, and faults there have accommodated indistinguishably the same amount of right slip (~65 km). Thus, it is also possible that dextral shear propagated rapidly northward from the juncture of the Mojave Desert block with the San Andreas fault system (Fig. 1). The youngest, least developed parts of the shear zone occupy the northern Walker Lane (e.g., Pyramid Lake and Modoc Plateau domains), where cumulative right slip decreases from ~25 km to zero northwestward toward the terminus of the shear zone in the southernmost Cascade arc. Discontinuous, en echelon dextral faults in this region indicate a relatively immature strike-slip fault system analogous to Riedel shears developing above a more through-going shear zone at depth. Most and possibly all dextral shear in the Pyramid Lake and Modoc Plateau domains postdates ~4 Ma. Thus, it is probable that the belt of dextral shear propagated northwestward through the northern Walker Lane since ~4 Ma.

GPS geodetic data show that current strain rates within active portions of the Walker Lane – eastern California shear zone in the western Great Basin average ~10 mm/yr (e.g., Gan et al., 2000; Oldow et al., 2001; Hammond and Thatcher, 2004, 2007), or ~20% of the relative dextral motion between the Pacific and North American plates. Assuming an onset of strike-slip faulting ~10 Ma, current strain rates would predict nearly 100 km of slip along most segments of the Walker Lane, much more than the 20-65 km observed in most regions. This suggests that strain rates have generally increased with time (± that some dextral shear was taken up by WNW extension in the Great Basin). It follows that the Walker Lane – eastern California shear zone is accommodating more plate motion today than during its early history.

Strain rates decrease significantly, however, near the northwestern terminus of the system in northeast California. As strain rates decrease to the northwest, dextral shear appears to diffuse into west-northwest-directed extension within the northwestern Great Basin, thus accentuating extension within this part of the Basin and Range province and inducing abundant geothermal activity. The transfer of dextral shear to extensional strain has probably characterized the long-term evolution of the Walker Lane – eastern California shear zone within the western Great Basin and greatly affected patterns of deformation in neighboring parts of the Basin and Range province and along the eastern front of the Sierra Nevada block. The westward migration of extension within the western Great Basin since 15-10 Ma may be partly related to the maturation of the dextral shear zone and concomitant increases in strain transfer and resultant northwest-directed extension.

Influence of plate-boundary events

Because the Walker Lane – eastern California shear zone is currently accommodating ~20% of the plate boundary motion, a critical question is whether its overall evolution can be linked to major plate boundary events (Table 1 and Fig. 13). Inception of the San Andreas fault system ~30 Ma appears to have had little effect on the Walker Lane. Although some strike-slip faulting may have begun as early as ~25 Ma in the central Walker Lane (Ekren et al., 1980;



Dilles and Gans, 1995), widespread dextral faulting within the Walker Lane – eastern California shear zone did not begin until middle to late Miocene time, long after initiation of the San Andreas system. This is not surprising as the San Andreas did not organize into a mature, through-going strike-slip fault system until the elimination of several microplates in coastal regions of southern California by ~16 Ma (Fig. 2B).

Early to middle Miocene plate boundary events greatly impacted early development of the Walker Lane – eastern California shear zone. These include the elimination of microplates in coastal California, significant southward steps in the Rivera triple junction at ~19-16 Ma and again at ~13 Ma, and an appreciable increase in relative plate motion ~12 Ma from 33 to 52 mm/yr. For example, the earliest deformation within the Walker Lane – eastern California shear zone occurred ~13 Ma within the Las Vegas and neighboring domains (i.e., eastern Walker Lane), essentially coincidental with the ~13 Ma south jump in the Rivera triple junction and ~12 Ma increase in plate motion (Fig. 13). We suggest that the lengthening and increasing organization of the San Andreas fault system that accompanied the early to middle Miocene elimination of microplates and southward steps in the Rivera triple junction, continued northward migration of the Mendocino triple junction, and the increase in relative plate motions all conspired to induce an inland transfer of dextral shear to the Las Vegas Valley shear zone ~13-12 Ma (and possibly also to the Stateline fault system). The apparent 8-9 mm/yr of dextral shear along the Las Vegas shear zone may have locally accounted for nearly 50% of the increase in relative plate motion. It is also noteworthy that the N60°W trend of the Las Vegas shear zone parallels the relative motion between the Pacific and North American plates prior to ~8 Ma.

Several subsequent events along the developing transform margin in late Miocene time further influenced the Walker Lane – eastern California shear zone (Fig. 13). One of the most critical was the inland shift of the southern part of the transform from the Tosco-Abreojos fault along the west coast of Baja California to the Gulf of California between ~13 and 6 Ma (Hausback, 1984; Stock and Hodges, 1989; Oskin et al., 2001; Oskin and Stock, 2003; Fletcher et al., 2007) and attendant development of the Big Bend in the San Andreas fault system (e.g., Powell et al., 1993; Ingersoll and Rumelhart, 1999). This coincided with a major change in plate motion from ~N60°W to N37°W between ~11 and 6 Ma (e.g., Atwater and Stock, 1998). Between ~11 and 6 Ma, dextral shear in the Walker Lane shifted westward from the N60°W-trending Las Vegas Valley shear zone to the north-northwest-trending belt in the western Great Basin (e.g., Mojave Desert domain, southern and central Walker Lane). We suggest that several factors induced this westward shift in activity. First, the north-northwest trend of the western Great Basin more closely paralleled the new N37°W direction of relative plate motion, as compared to the N60°W-trending Las Vegas shear zone. The average strike of currently active dextral faults in the eastern California shear zone and Walker Lane (southern, central, and northern parts) is N36°W, essentially identical to the N37°W direction of relative Pacific – North American plate motion. In addition, the beginning of transform motion in the Gulf of California would have placed the entire western Great Basin in a more favorable position to accommodate plate boundary motion (Figs. 1 and 3), because it was situated ~N30°W of the Gulf, approximately parallel to plate motion, and could ultimately link with the Gulf via a series of right steps or pull-aparts mimicking the style of deformation in the Gulf. Furthermore, the Big Bend in the San Andreas system would have impeded plate motion to the west. Thus, the path between the western Great Basin and Gulf of California would more closely follow a small circle while also avoiding the bottleneck of the Big Bend (e.g., Nur et al., 1993). The Las Vegas shear zone was essentially abandoned, because it was no longer favorably oriented relative to Pacific – North American plate motion and its growth to the southeast had been constrained by stronger, less mobile crust. As evidenced by longer fault lengths and possibly greater magnitude of right slip (compared to other parts of the Walker Lane), dextral shear in the western Great Basin may have begun in the southern Walker Lane and rapidly migrated to both the north and south. Proximity to the Las Vegas Valley shear zone to the east and a relatively simple, well-organized part of the San Andreas system in central California to the west may have favored this part of the western Great Basin for initial movement (Figs. 1 and 2C). Given current uncertainties, however, strike-slip faulting may have begun essentially contemporaneously from the Mojave Desert domain on the south to the Carson domain on the north (Table 1). Also, faulting may have propagated northward from the northern Gulf of California. By contrast, the northern Walker Lane may have developed somewhat later at ~4 Ma. The later onset of strike-slip faulting in these northern reaches is probably related to the recent offshore passage of the Mendocino triple junction, which has migrated through these latitudes since ~5 Ma (Fig. 2D, E). We therefore suggest that the Walker Lane is currently migrating northwestward roughly in concert with the ~3 cm/yr northward migration of the Mendocino triple junction (e.g., Faulds and Henry, 2006, 2007).

The less organized pattern of faulting within the Mojave Desert domain compared to the southern Walker Lane could be considered counterintuitive considering proximity to the San Andreas fault. However, this proximity may actually stymie development of more through-going faults in the Mojave block. For example, Dolan et al. (2007) showed that recent faulting in the Mojave region alternates with that along other parts of the San Andreas system (e.g., Los Angeles basin). As this switch is turned on and off, strain may not easily reset in the same location within the Mojave domain, as this may depend on which segments of the San Andreas have recently ruptured and the related transitory concentrations of stress. These complications may account for the broad zone of dextral shear within the Mojave Desert domain, which is nearly twice as wide as most other parts of the Walker Lane – eastern California shear zone (Table 1).

Future development of Walker Lane – eastern California shear zone

Several features indicate that the Walker Lane has been progressively lengthening and accommodating increasingly greater amounts of the Pacific – North American relative motion through time. These include the apparent younging of deformation to the north, the lower than expected magnitude of right slip given current strain rates and timing of deformation, and the propensity of the San Andreas system to periodically jump inland and transfer parts of North America to the Pacific plate, as best exemplified by the eastward shift of the southern part of the system into the Gulf of California during the late Miocene. The present character of the Walker Lane may resemble the proto-Gulf of California (12-6 Ma), whereby significant dextral shear was accommodated on poorly organized systems of dextral faults. Today, the Mendocino triple junction and San Andreas fault system are propagating northward at ~3 cm/yr (Atwater and Stock, 1998), while the Walker Lane appears to be growing northward in concert with the San Andreas. Continued northward migration of the Mendocino triple junction puts it on a collision course with the northwest-propagating Walker Lane off the southern Oregon coast in ~7-8 Ma (i.e., in the future; Fig. 2E, F). Although east-west to northwest-directed extension within the Basin and Range will continue moving the western edge of North America outward, this should not greatly impede the eventual collision between the triple junction and north end of the Walker Lane, as the current westward component of extension in the Basin and Range (e.g., Thatcher et al., 1999; Bennett et al., 2003) is much less than the apparent 3 cm/yr northward propagation of the Walker Lane.

This collision may herald a significant inland jump of the plate boundary to the Walker Lane – eastern California shear zone. Assuming that other re-arrangements do not occur, the Walker Lane may represent a more stable configuration for accommodating large-magnitude dextral shear, because its trace would avoid the bottleneck at the Big Bend in the San Andreas and also better fit a small circle path compared to the current trace of the San Andreas (Figs. 1 and 2E, F). East-west extension during development of the transform boundary has probably partly facilitated the inland migration of the San Andreas fault system, because the area near the middle of the evolving transform has undergone greater extension than that near the triple junctions. Thus, the transform plate boundary has probably grown increasingly convex outward, making an eastern path a better fit for a small circle. Large magnitude extension within much of the Basin and Range (e.g., >100 km near Las Vegas; Wernicke and Snow, 1998) suggests that this process has greatly affected the configuration of the transform plate margin. We therefore suggest that the Walker Lane – eastern California shear zone will ultimately evolve into the primary transform boundary between the Pacific and North American plates shortly after the triple junction and north end of the shear zone coalesce off the southern Oregon coast in ~7-8 Ma (Fig. 2F and 13)

Broad implications

Models for the future development of the transform margin are obviously speculative, but they do help to demonstrate some of the broader implications of studying and synthesizing various parts of the Pacific – North American plate boundary. For example, the current tectonic setting represents one stage in the progressive dismembering of an Andean type margin through continued lateral growth and inland propagation of an evolving transform boundary. This process is slowly fragmenting the western margin of North America and transferring large slices of the continent to the largely oceanic Pacific plate. Baja California has already been entirely transferred to the Pacific Plate, and much of California may follow in ~7-8 Ma. Parts of the Pacific Northwest may ultimately have a similar fate, assuming continued northward propagation of the Mendocino triple junction and additional inland jumps of the transform boundary. A longer transform would ultimately generate a broader region of dextral shear within the continental lithosphere, making inland (or continent-ward) jumps of the transform and such fragmentation more likely through time. Southern Alaska may be the ultimate resting ground for the terranes produced along this transform boundary.

Accordingly, evolving transform faults may be an efficient means by which to generate numerous exotic (i.e., far-traveled) terranes, which may ultimately dock at convergent plate boundaries thousands of kilometers from their origin. This process may be more efficient at dismembering the margin of a continent and producing exotic terranes than rifting and drifting. It may therefore represent an important underappreciated process in plate tectonics, whereby oblique rifting and evolving transforms facilitate both the orogenic collapse and fragmentation of convergent plate margins. The exotic terranes produced at the transform boundaries eventually dock at convergent plate margins and can thereby induce major orogenies, which may ultimately collapse and fragment as new transform boundaries develop. Such a sequence of events is broadly analogous to Wilsonian-cycle tectonics (e.g., Dewey and Burke, 1974), but with significant differences resulting from the lateral mobility of the exotic terranes along transform boundaries. Thus, analysis of the Walker Lane – eastern California shear zone has implications both for understanding how strike-slip fault systems initiate and eventually organize and mature into major transform faults at one scale, while also providing insights into the fragmentation of continents and production of exotic terranes at a much broader scale.

ACKNOWLEDGMENTS

This work was supported by grants from the National Science Foundation (EAR0124869), Department of Energy (DE-FG36-02ID14311), and STATEMAP program of the U.S. Geological Survey. We have benefited from fruitful discussions with Ernie Anderson, Tanya Atwater, Sue Beard, John Bell, Craig dePolo, Bill Dickinson, Ernie Duebendorfer, Larry Garside, Nick Hinz, Gene Humphreys, Corné Kreemer, Jeff Lee, John Oldow, Jack Stewart, Danny Stockli, and others on various aspects of the Pacific – North American transform boundary and geologic relations in different parts of the region. We thank Kris Pizarro for help in preparing several of the figures. Constructive reviews by Nick Hinz, Inga Moeck, and Jon Spencer improved this manuscript.

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